11th International Workshop on the Physics of Excited Nucleons (NSTAR2017), Columbia, SC, August 20-23, 2017

Topics covered in the workshop are:

- Baryon spectrum through meson photoproduction
- Baryon resonances in experiments with hadron beams and in the e+e- collisions
- Baryon resonances in ion collisions and their role in cosmology
- Baryon structure through meson electroproduction, transition form factors, and time-like form factors
- Amplitude analyses and baryon parameter extraction
- Baryon spectrum and structure from first principles of QCD
- Advances in the modeling of baryon spectrum and structure
- Facilities and future projects
- Other topics related to N* physics


OLYMPUS
CELESTRON

11th International Workshop on the Physics of Excited Nucleons (NSTAR2017), Columbia, SC, August 20-23, 2017

14:00 – 15:30		Parallel Session (C2) DMSB 126 Chair: Douglas Hasell
	C2: 14:00	Michael Kohl, "Experimental Advances in Two-Photon Contributions to Lepton-Proton Scattering"
	C2: 14:30	Mikhail Yurov, "Two-photon exchange contribution to elastic electron-proton scattering"
	C2: 14:50	Oleksandr Koshchii, "Lepton mass effects in two-photon exchange theory"
	C2: 15:10	Oleksandr Tomalak, "Two-photon exchange correction in elastic lepton-proton scattering. Dispersive and model calculations"
16:00 – 17:50		Parallel Session (C3) DMSB 126 Chair: Douglas Hasell
	C3: 16:00	Peter Blunden, "Overview of recent theoretical work on two-photon exchange"
	C3: 16:30	Egle Tomasi-Gustafsson, "Two-photon exchange: myth and history"
	C3: 16:50	Jan Bernauer, "Two-Photon-Exchange: Future experimental prospects"
	C3: 17:10	Joseph Grames, "Polarized Positron Beam R&D at Jefferson Lab"
	C3: 17:30	Fred Myhrer, "Lepton bremsstrahlung at low energies"

Experimental Advances in Two-Photon Contributions to Lepton-Proton Scattering

Michael Kohl <kohlm@jlab.org> *

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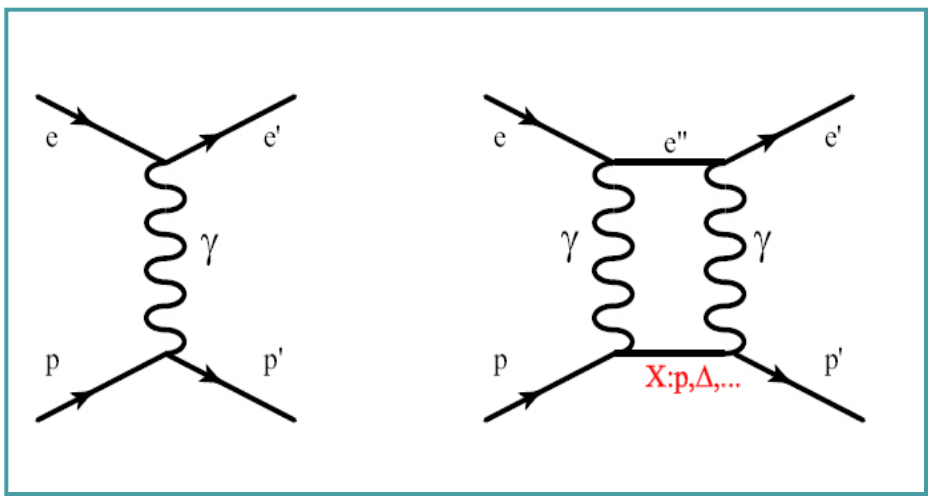
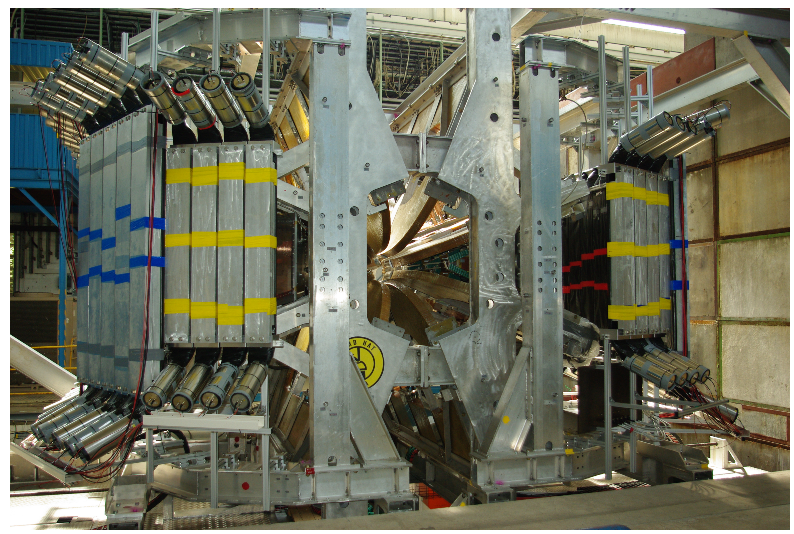
Jefferson Laboratory, Newport News, VA 23606

* **Presently supported by DOE DE-SC0013941, NSF HRD-1649909, PHY-1505934 and PHY-1436680**

Outline

- Proton form factors in the context of one-photon exchange (OPE)
- The limit of OPE or:
  - What is G_E^p ?
  - What is the nature of lepton scattering?
- Two-photon exchange (TPE): New observables
- Current and future experiments to probe TPE
  ➔ OLYMPUS & more
- Latest Review:
  A. Afanasev, P.G. Blunden, D. Hasell, and B.A. Raue, PPNP 95, 245 (2017)





OLYMPUS @ DESY

Nucleon elastic form factors …

- Fundamental quantities
- Defined in context of single-photon exchange

- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism

- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Role of orbital angular momentum and diquark correlation
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments

G. Miller,
PRC68, 022201 (2003)

60+ years of ever increasing activity

- Considerable progress in experiment and theory over last two decades
- New techniques / polarization experiments
- Unexpected results

Proton form factor and TPE experiments

Recoil polarization and polarized target (Jlab)

E04-108 – high-Q^2 recoil polarization (GEp-III) – published (2010)
E04-019 – ε dependence of recoil pol. (2-Gamma) – published (2011)
E08-007 – part I: low-Q^2 recoil polarization – published (2011)
E08-007 – part II: low-Q^2 polarized target – analysis in progress
E07-003 – high-Q^2 polarized target (SANE) – to be published
E12-07-109 – high Q^2 recoil pol. (GEp-V/SBS) – in preparation

Unpolarized cross sections (Jlab)

E05-017 – high-Q^2 Rosenbluth (Super-Rosen) – first results, to be published
E12-07-108 – high-Q^2 unpolarized (GMp) – first results, to be published

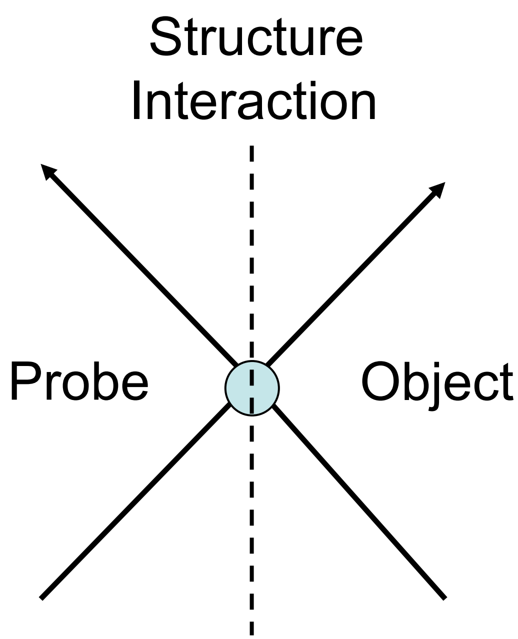
Positron-electron comparisons

Novosibirsk/VEPP-3 – published (2015)
CLAS/JLab – published (2015+2017)
OLYMPUS/DESY – published (2017)

Proton radius measurements

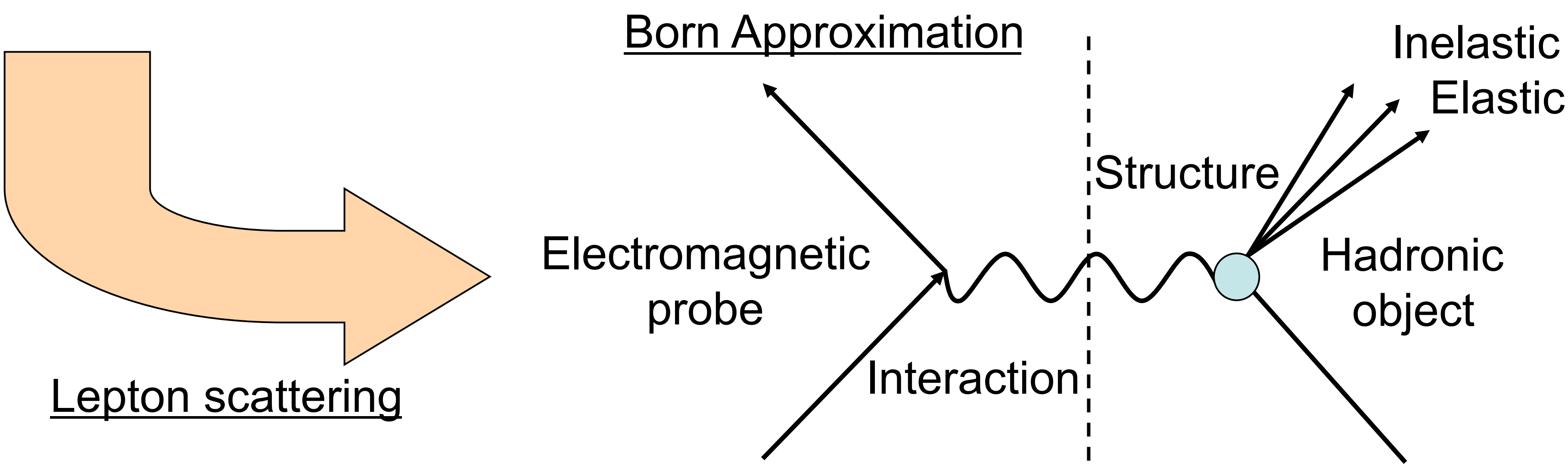
PSI / (muonic hydrogen Lamb shift, HFS) – published (2010, 2013)
MAMI / A1 (e-scattering) – published (2010+2014)
MAMI / A1 (ISR) – published (2017), t.b. cont'd
Jlab / PRad (e-scattering) – analysis in progress
PSI / MUSE ($e^\pm$, $\mu^\pm$ scattering) – in preparation

Hadronic structure and EM interaction



Factorization!

$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$



One-Photon Exchange Approximation

The beginnings

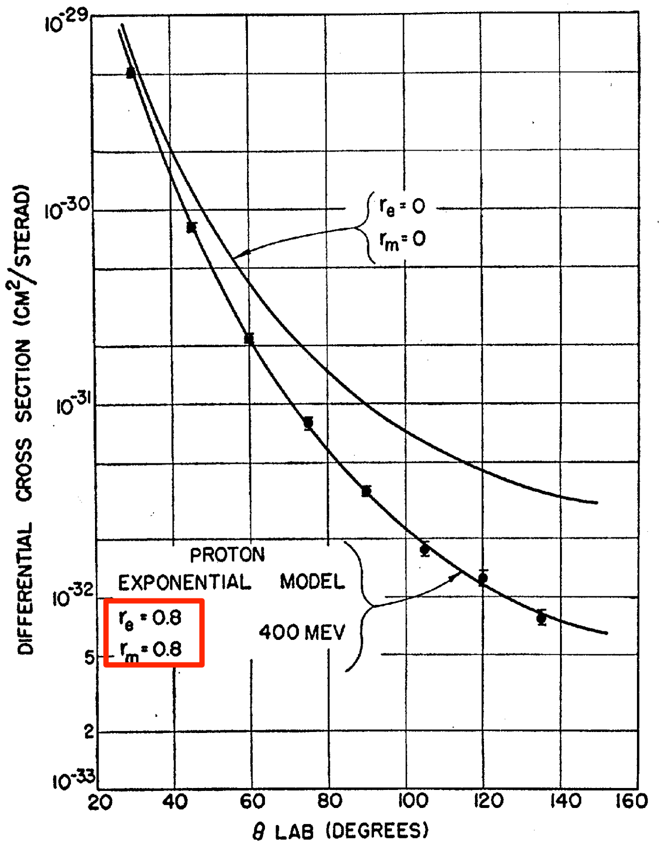


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

Robert Hofstadter
Nobel prize 1961

ep-elastic
finite size of the proton
$R_p \sim 0.8$ fm

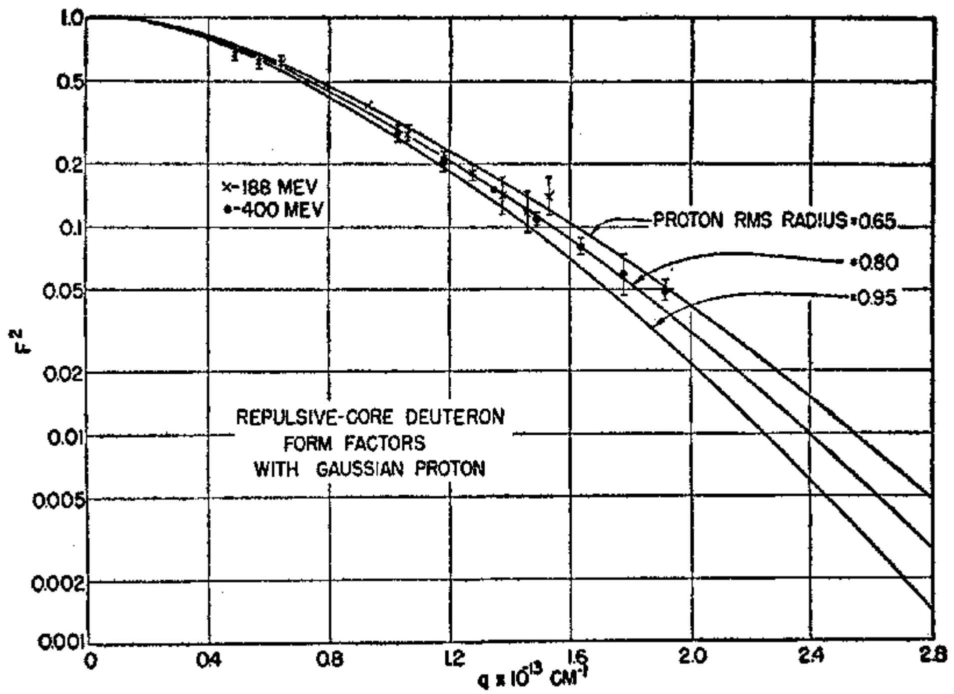
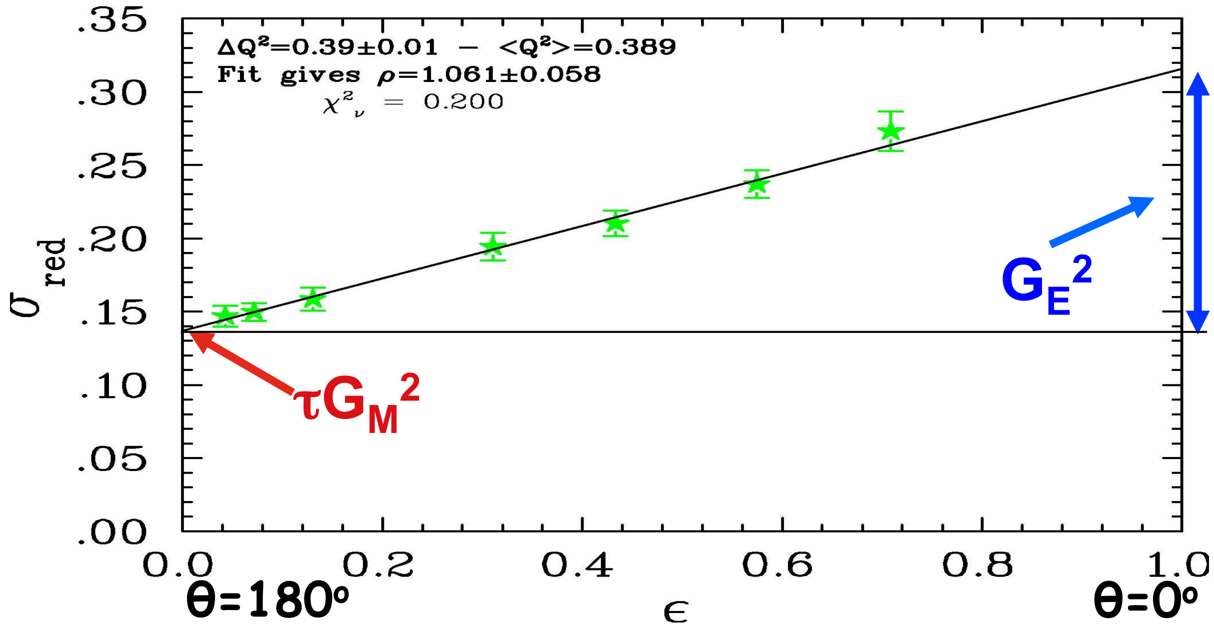


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Form factors from Rosenbluth method



$\sigma_{red} = \varepsilon G_E^2 + \tau G_M^2$

→ Determine
$|G_E|$, $|G_M|$, $|G_E/G_M|$

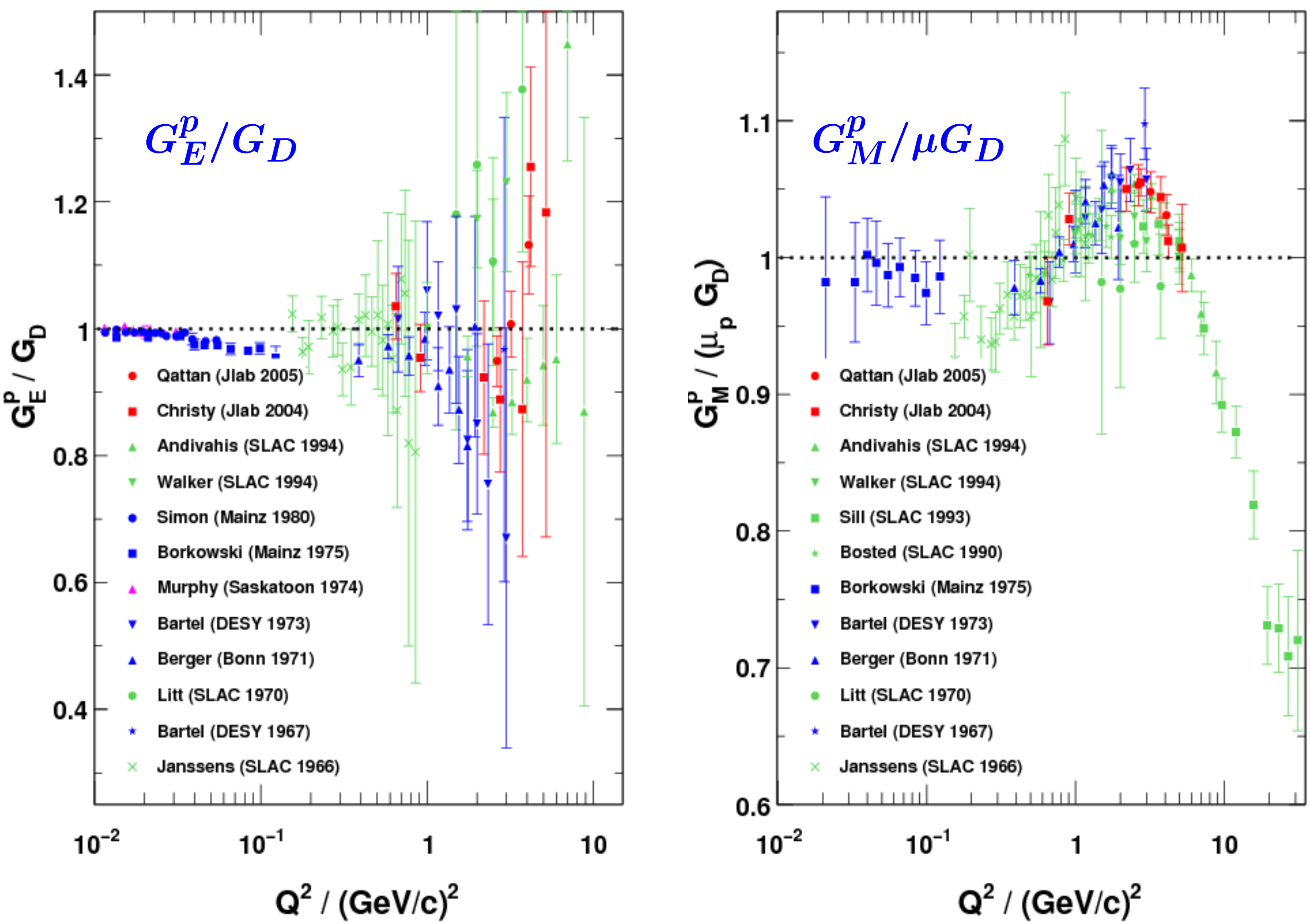
- In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

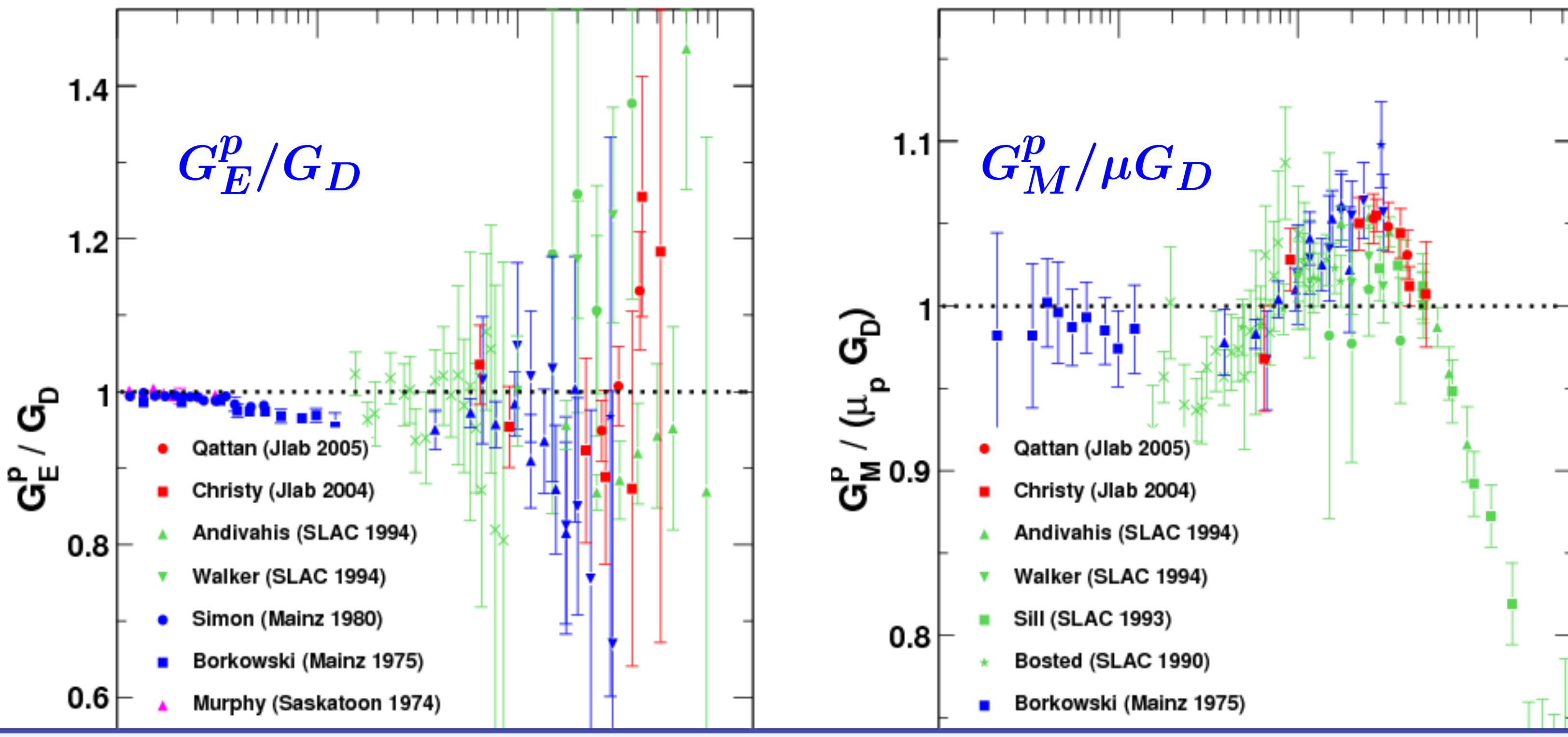
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon\,(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

G^p_E and G^p_M from unpolarized data



G^p_E and G^p_M from unpolarized data

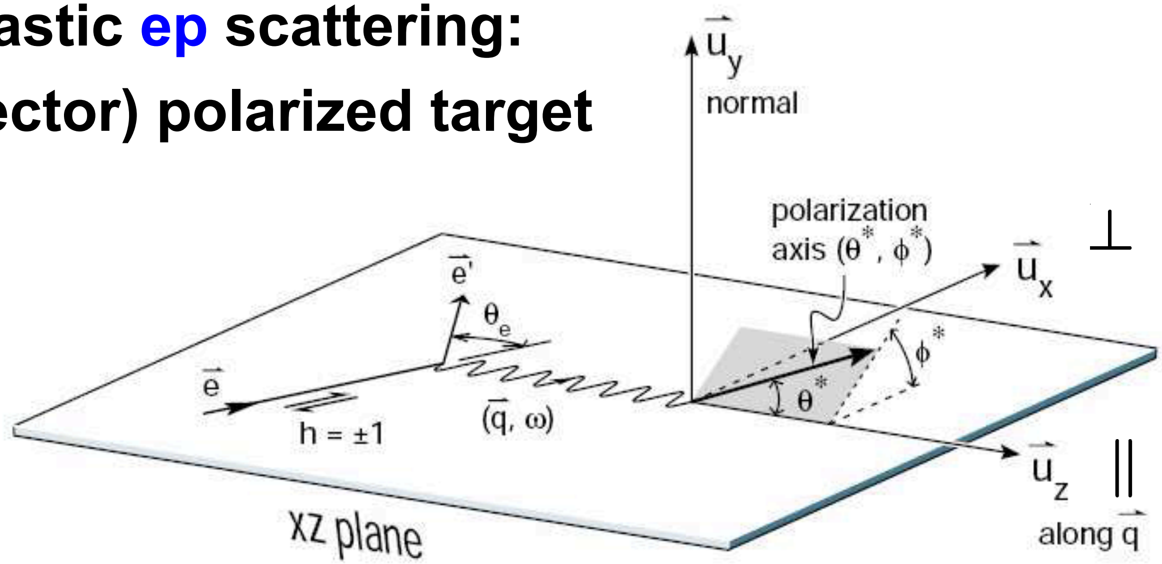


- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ **charge and magnetization density (Breit fr.)**
- **Dipole form factor** $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \quad \longleftrightarrow \quad \rho_D(r) = \rho_0\, e^{-\sqrt{0.71}r}$
- $G^p_E \approx G^p_M/\mu_p \approx G^n_M/\mu_n \approx G_D$ **within 10% for $Q^2 < 10$ (GeV/c)^2**

Nucleon form factors and polarization

- **Double polarization in elastic ep scattering: Recoil polarization or (vector) polarized target**

  $^1H(\vec{e},e'\vec{p})$, $^1\vec{H}(\vec{e},e'p)$



- **Polarized cross section**

$$\sigma = \sigma_0 \left(1 + P_e \vec{P}_p \cdot \vec{A}\right)$$

- **Double polarization observable = spin correlation**

$$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*$$

- **Asymmetry ratio ("Super ratio")**

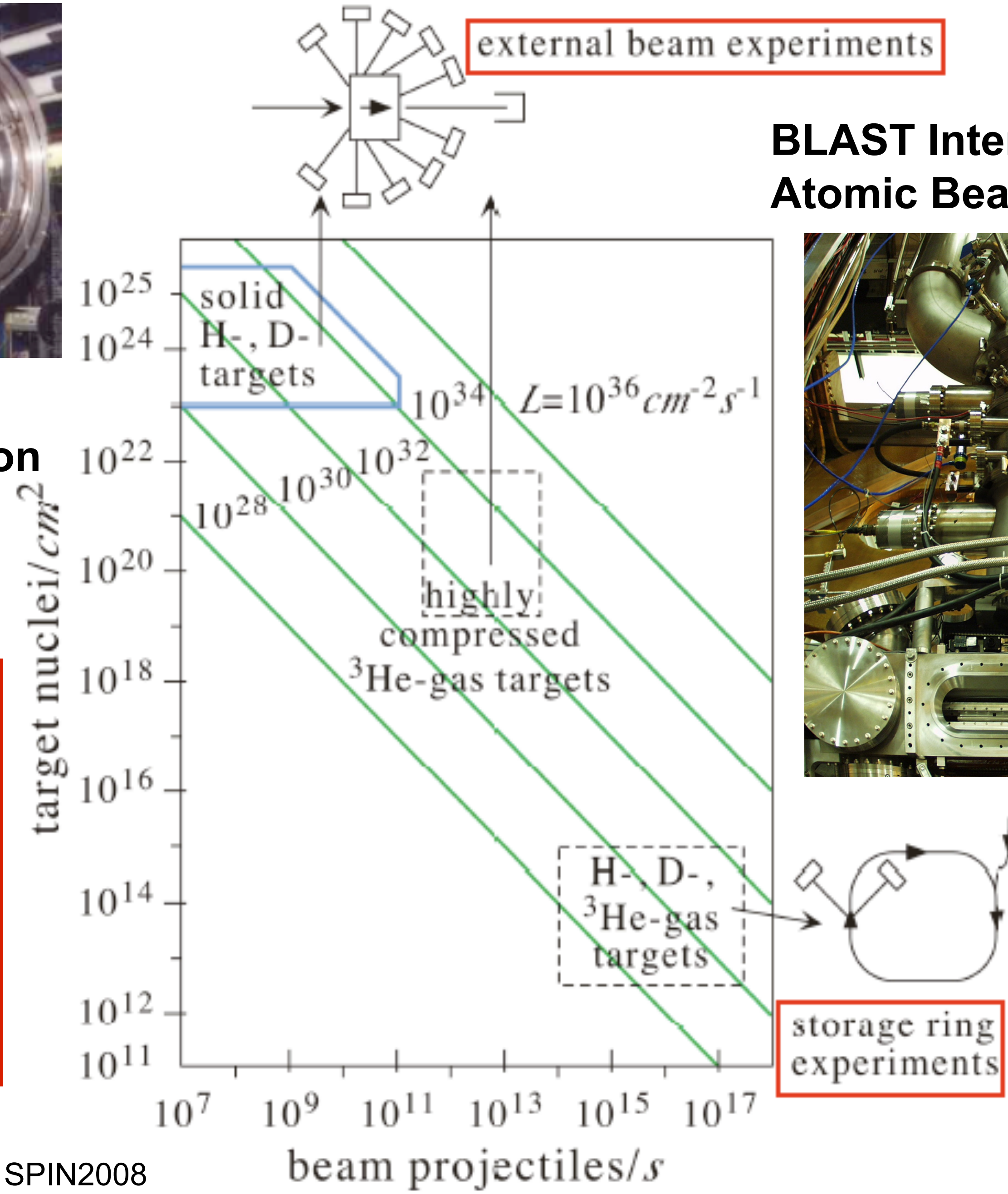
$$\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$$

independent of polarization or analyzing power

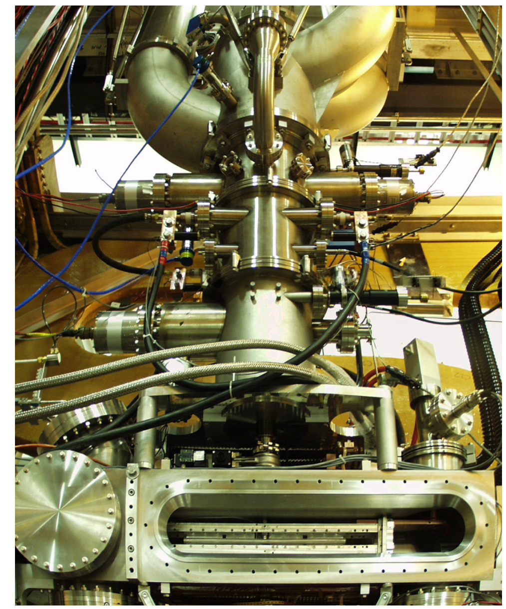
Dombey (1969)
Donnelly and Raskin (1986)

Polarized targets

UVA / "SLAC"-Target: Dynamic Nuclear Polarization



BLAST Internal Target: Atomic Beam Source

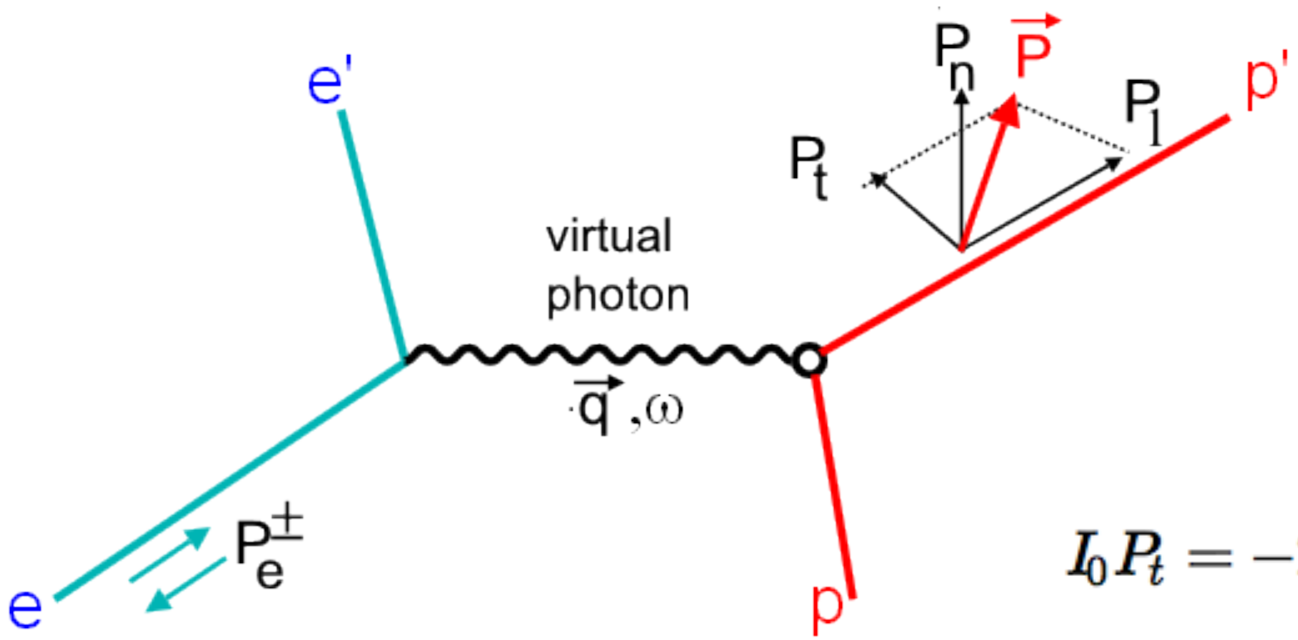


Limited luminosity for polarized hydrogen/ deuterium targets

Very precise at low to moderately high Q^2

from W. Meyer, SPIN2008

Recoil polarization technique



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_\ell = \frac{1}{M}(E_e + E_e')\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_e + E_e')}{2M_p}\tan(\frac{\theta_e}{2})$$

$$I_0 \propto G_E^2 + \frac{\tau}{\epsilon}G_M^2$$

<u>Applicable to protons and neutrons</u>

Akhiezer and Rekalo (1968+1974)
Arnold, Carlson and Gross (1981)

Recoil polarization technique

- Pioneered at MIT-Bates
- Pursued in Halls A and C, and MAMI A1
- In preparation for Jlab @ 12 GeV

V. Punjabi *et al.*, Phys. Rev. C 71, 05520 (2005)

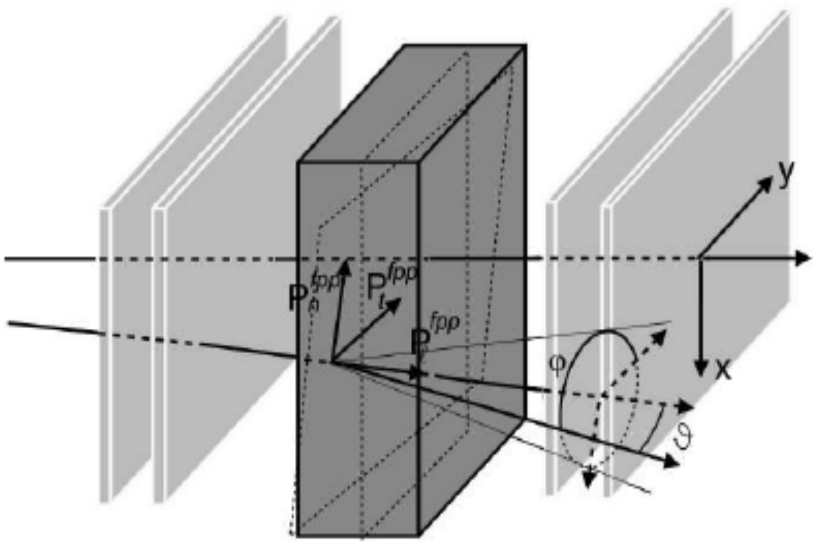


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

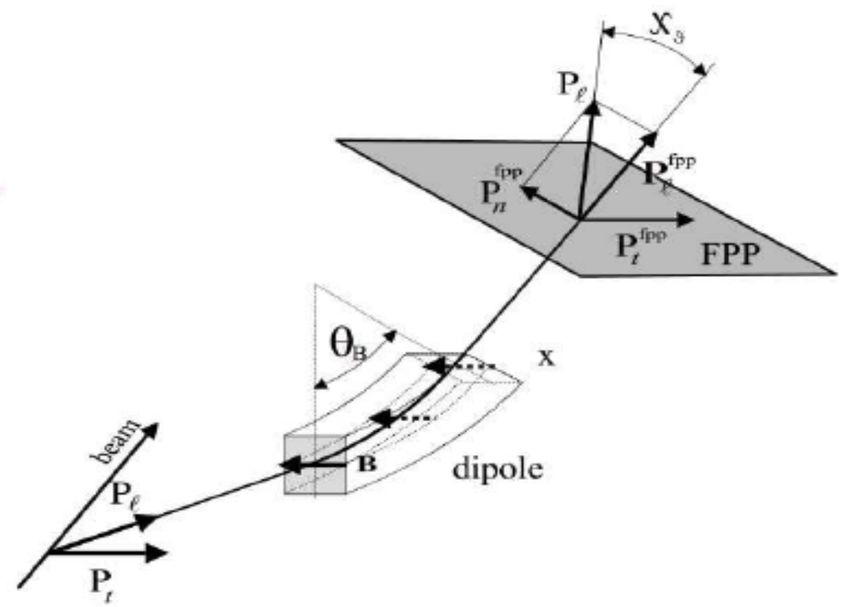
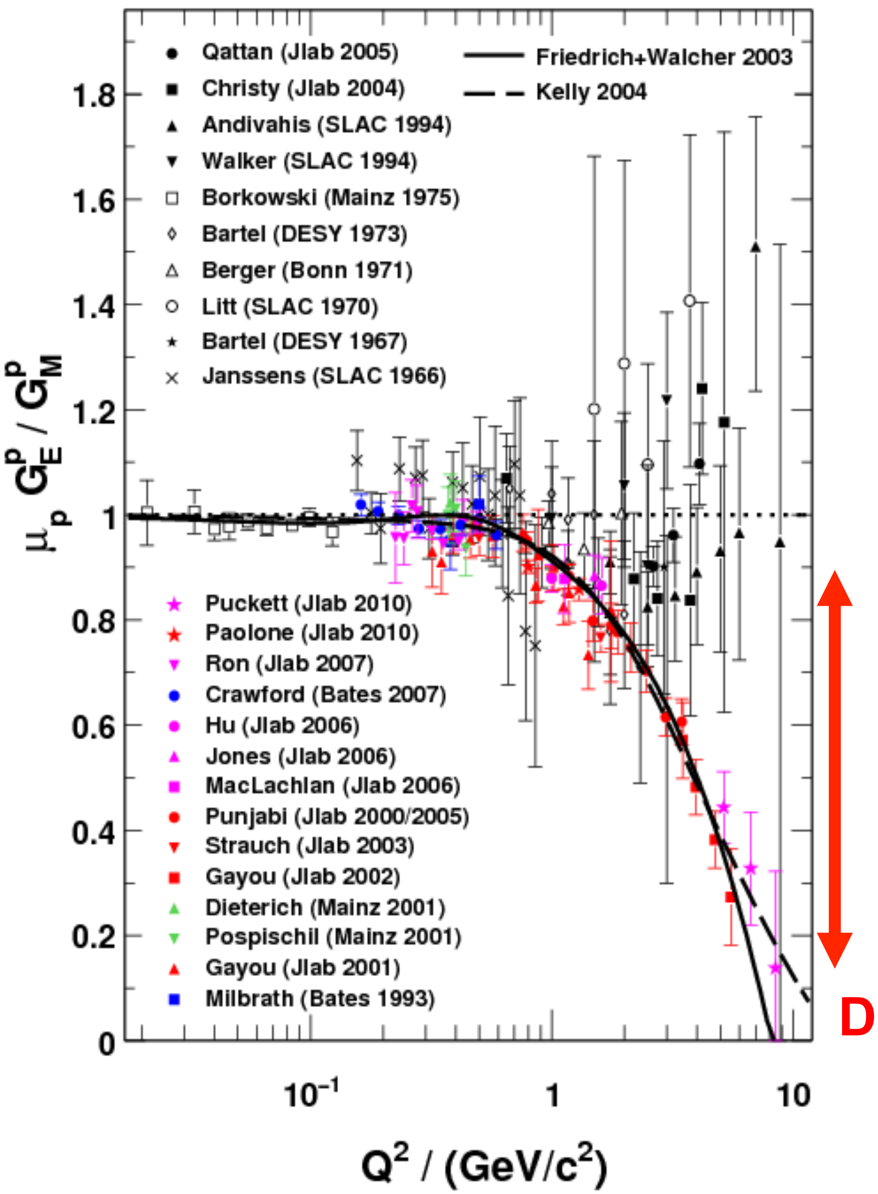


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

Focal-plane polarimeter
Secondary scattering of polarized proton from unpolarized analyzer

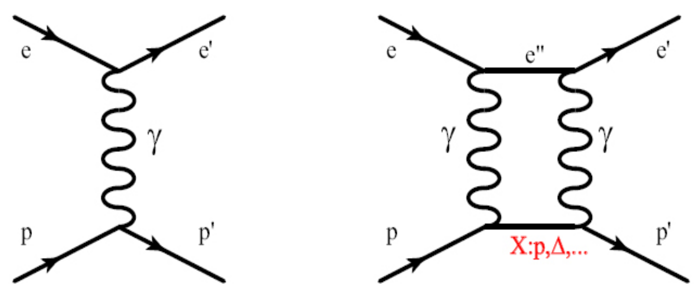
Spin transfer formalism to account for spin precession through spectrometer

Proton form factor ratio



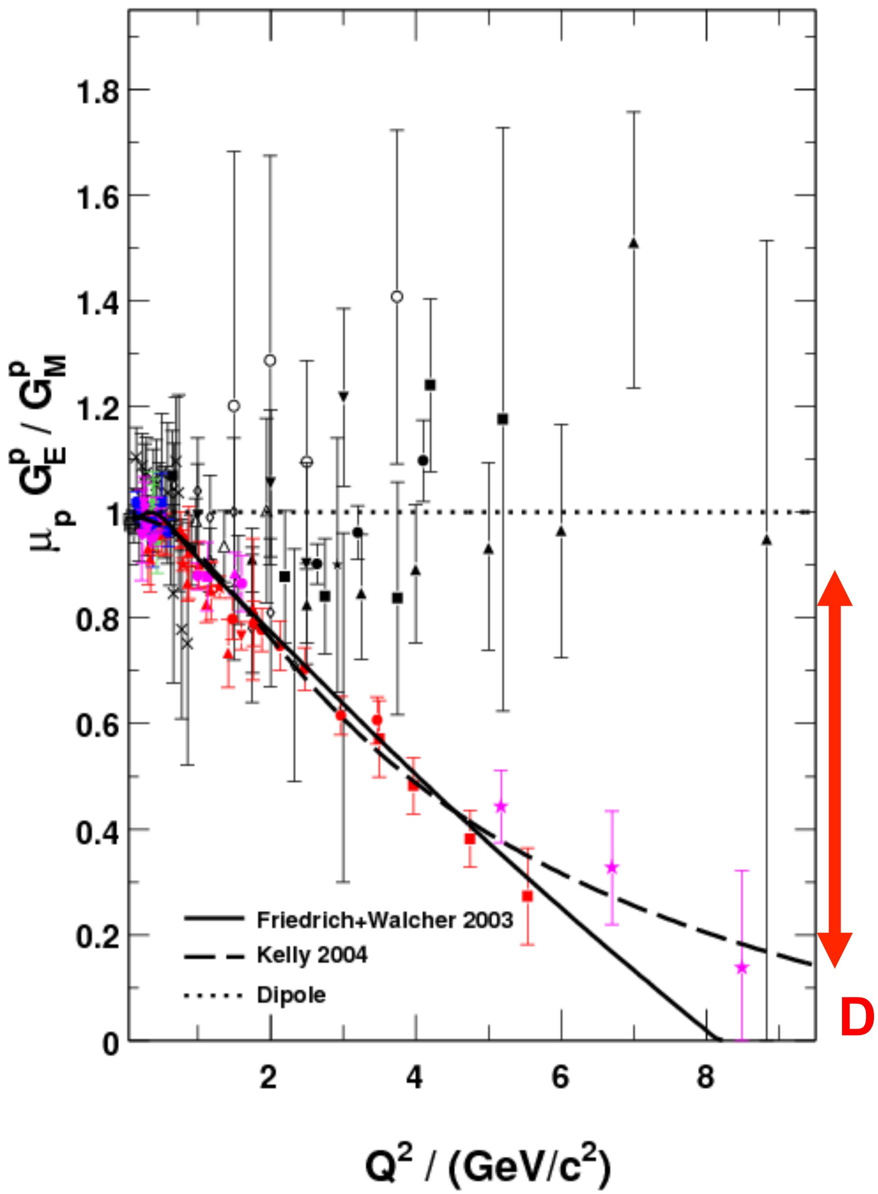
Jefferson Lab 2000–

- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



>800 citations

Proton form factor ratio



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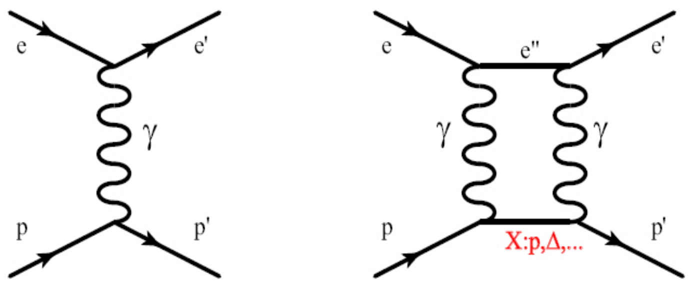
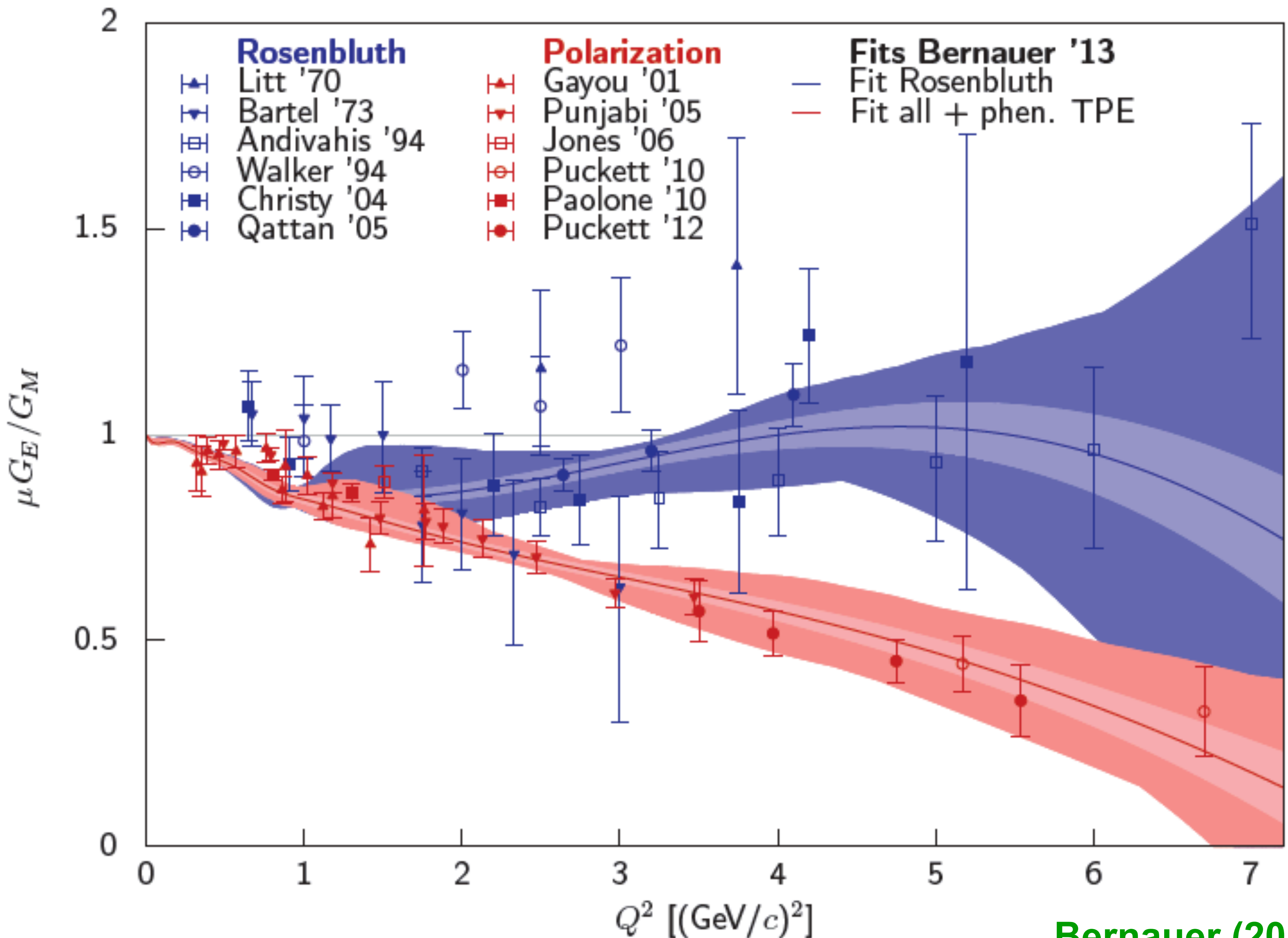


Dramatic discrepancy!

>800 citations

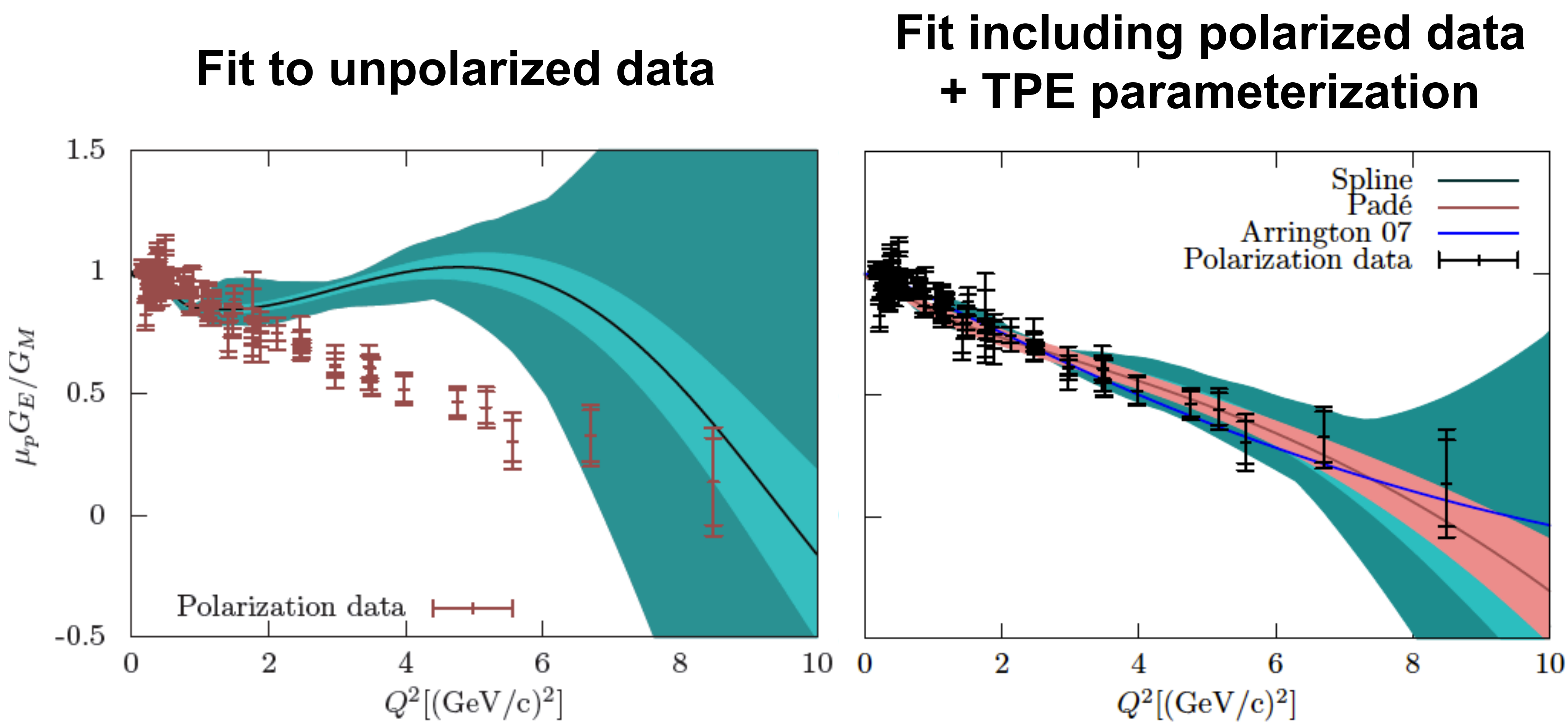
Another look



Bernauer (2014)

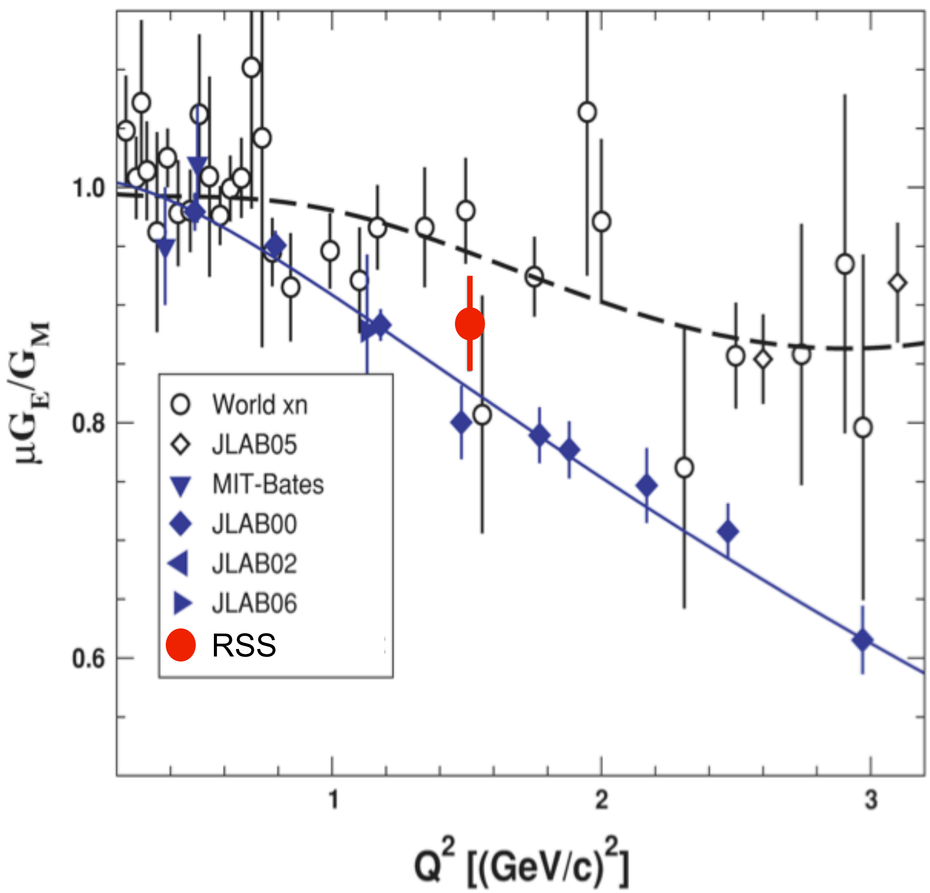
No discrepancy below $Q^2 < 2$ (GeV/c)^2 ?

Global analysis



J.C. Bernauer *et al.*, PRC 90, 015206 (2014) [arXiv:1307.6227v2]

Polarized target data at high Q^2



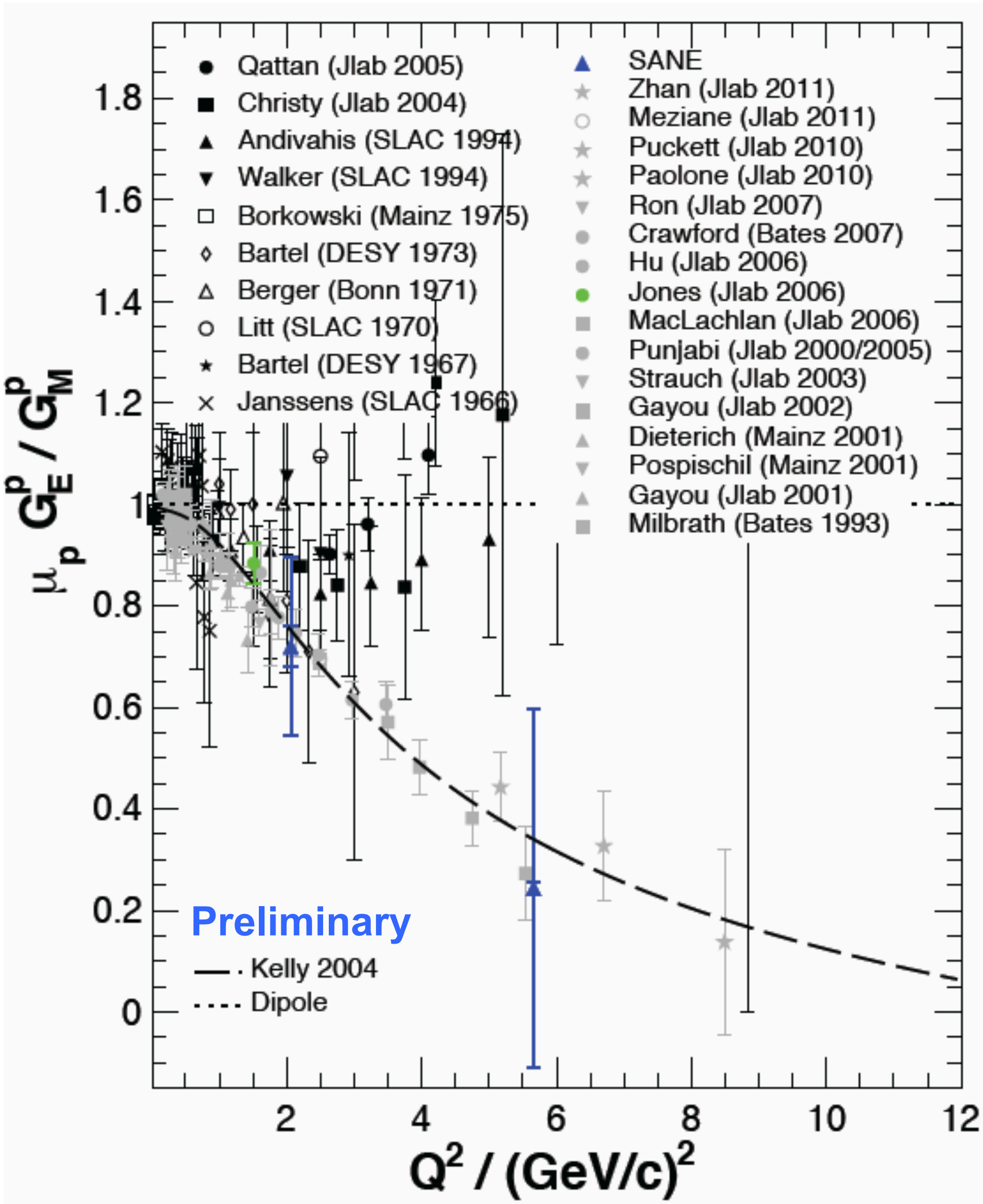
Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
Q^2<0.65 (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

M.K. Jones *et al.*, PRC74, 035201 (2006)

Polarized target data at high Q^2



A. Liyanage, M.K. *et al.*, to be published

Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
$Q^2 < 0.65$ (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
G_E/G_M at $Q^2 \approx 2.1$ and 5.7 (GeV/c)^2

Decline of G_E/G_M has been confirmed!

Future precision measurements at high Q^2 are feasible

New unpolarized data at high Q^2

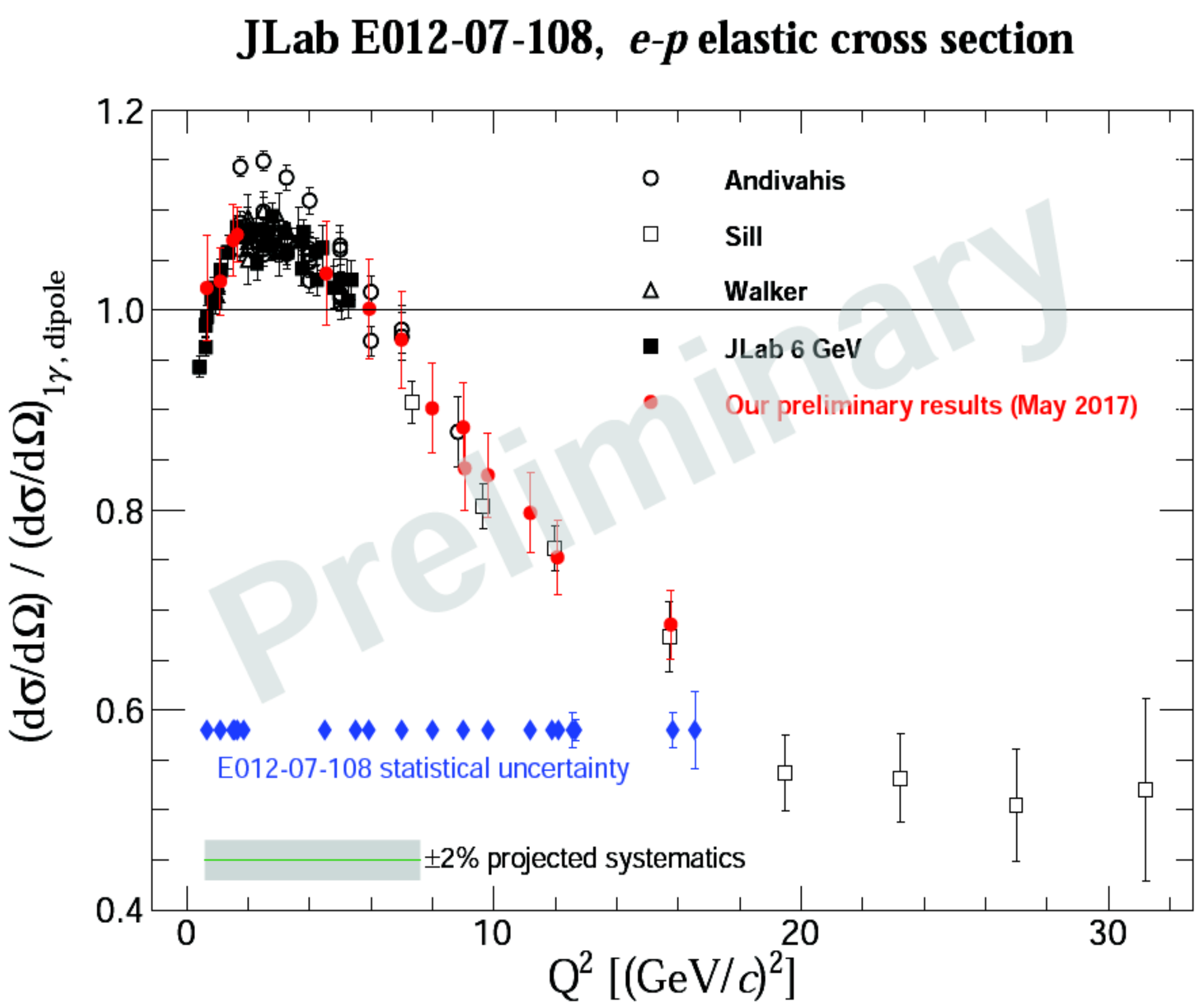
- **GMp (E12-07-108):**
  Magnetic form factor of the proton at high Q^2 (cross section)
  Scattered electron detection (single-arm)
  Data taking completed in 2016
  Preliminary results available
  Final results by spring 2018

- **Super-Rosen (E05-017):**
  High-Q^2 Rosenbluth separation up to $Q^2 < 5.7\ (GeV/c)^2$
  Recoil proton detection (single-arm)
  Presentation by M. Yurov following this talk

E012-07-108 Experiment

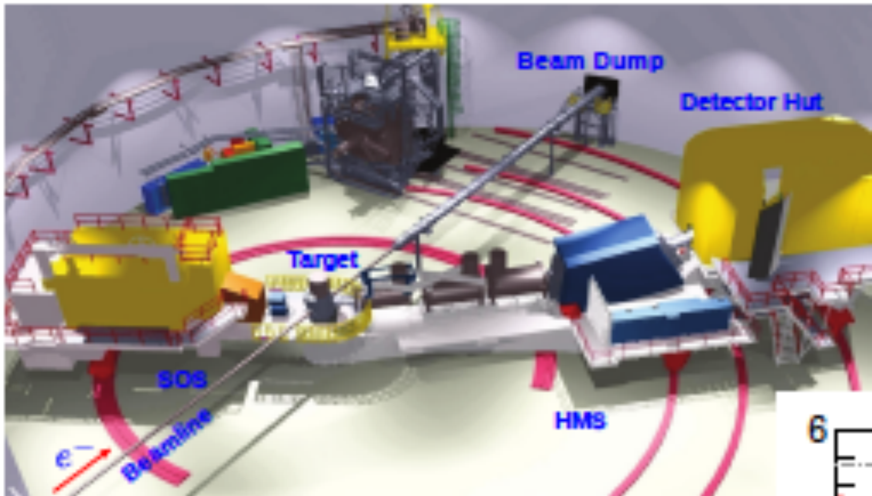
Precision Measurement of the Proton Elastic Cross-Section at High Q^2

- Precision e-p elastic cross-section is necessary to:
  - Constrain two-photon exchange (TPE) contribution through global analysis
  - Determine GEp, GMp and TPE contributions at high Q^2, in combination with polarization measurements
  - Find absolute form factor values from 12-GeV era JLab experiments
- Preliminary cross-section results are presented below with 5% uncertainty (total)
- Final results will be available by spring 2018 with better than 2% systematic uncertainty



E. Christy

E05-017 HALL C, JLAB



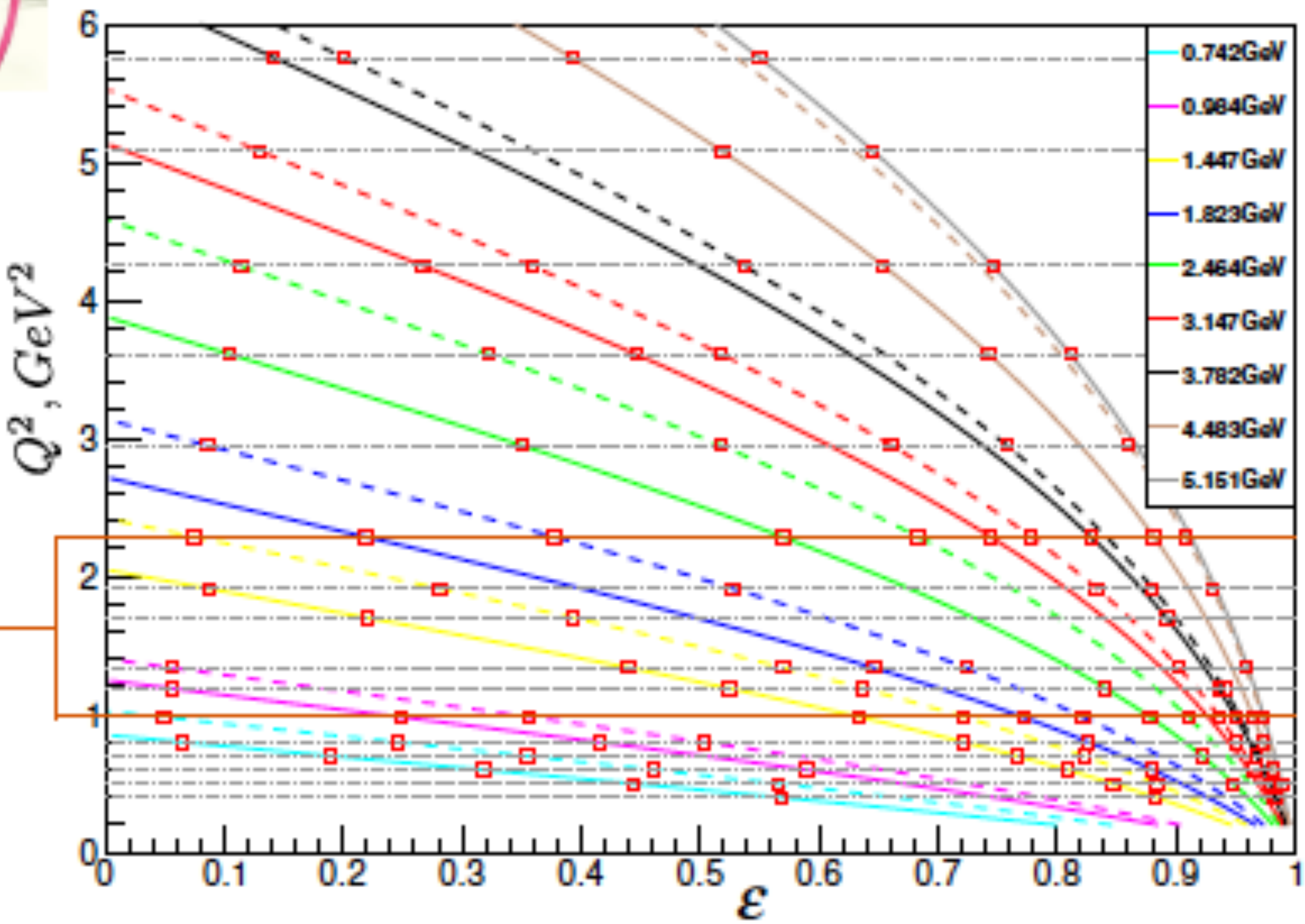
Experimental Hall C Layout

- 4 cm LH2 and dummy targets
- recoil proton detected in HMS
- 17 settings of beam energy

102 Kinematics points

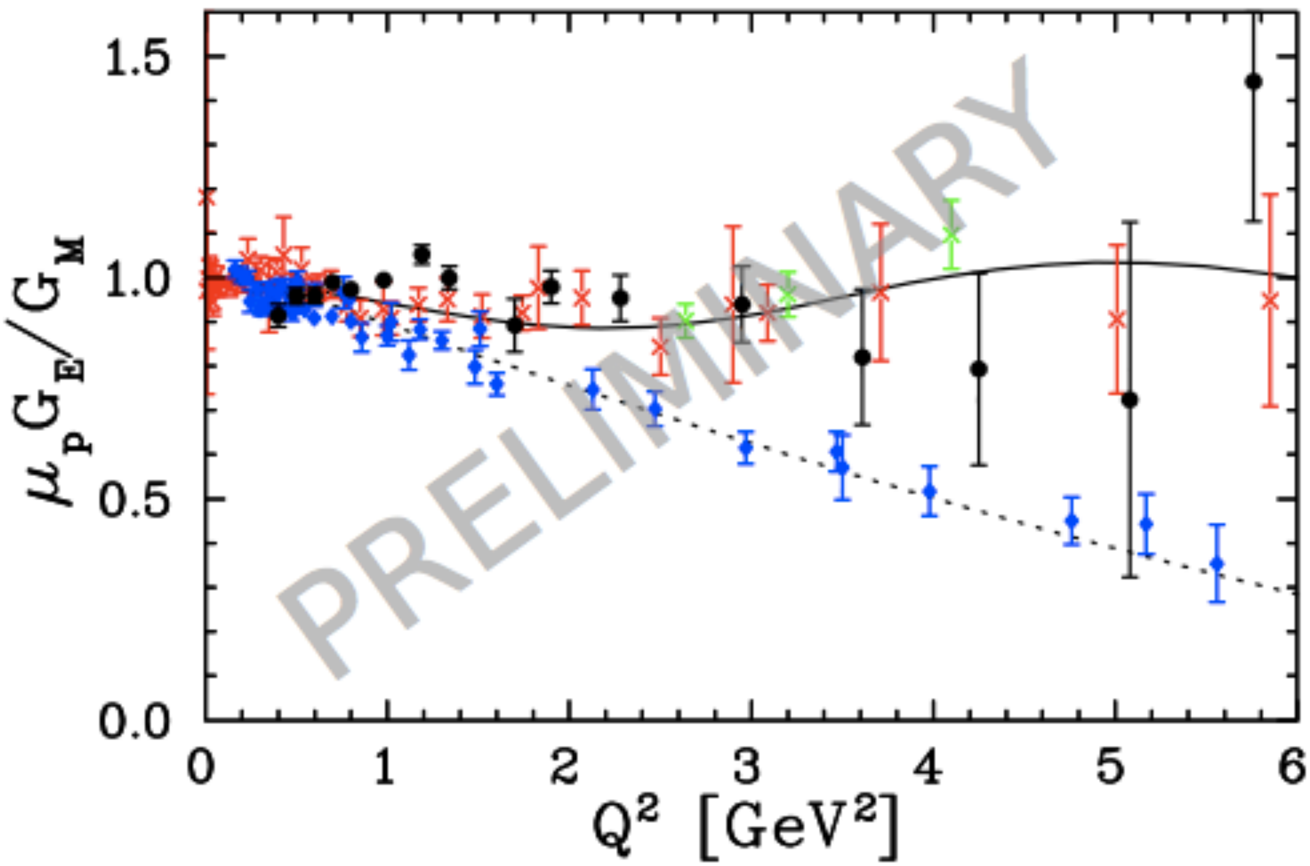
10 points at $Q^2 = 2.284$

13 points at $Q^2 = 0.983$



PRELIMINARY RESULTS

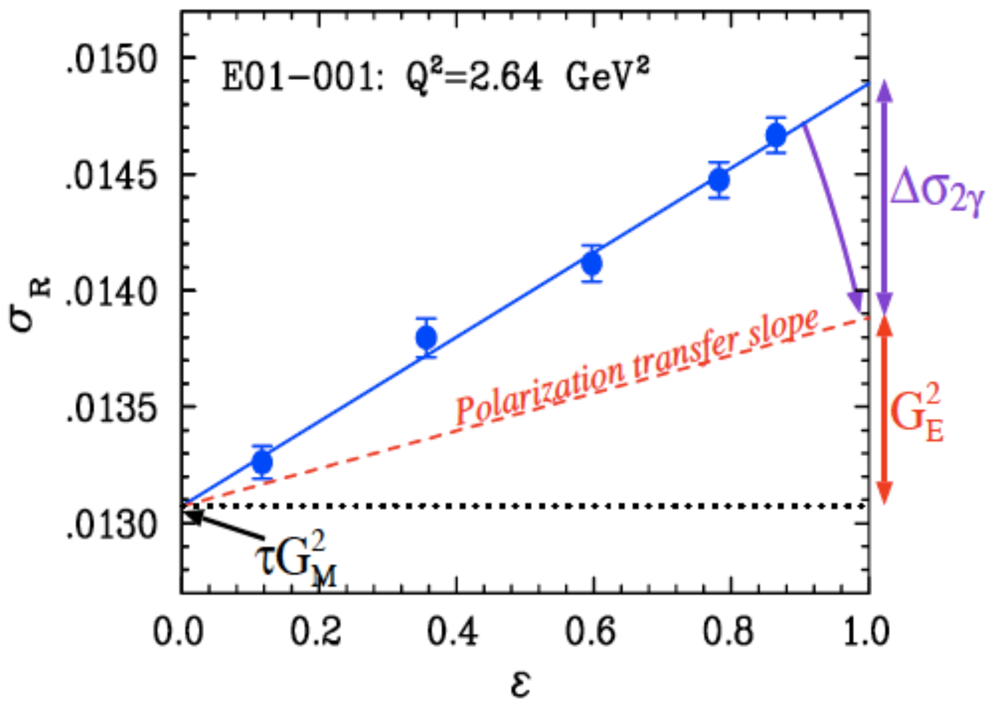
- $\mu_p G_E/G_M$ extraction:
  - from analysis that focused on low Q^2 settings
- expected uncertainty reduction:
  - slope by factor of 2 everywhere
  - point-to-point by factor 1.3 at $Q^2 < 2$ and by 1.5 above

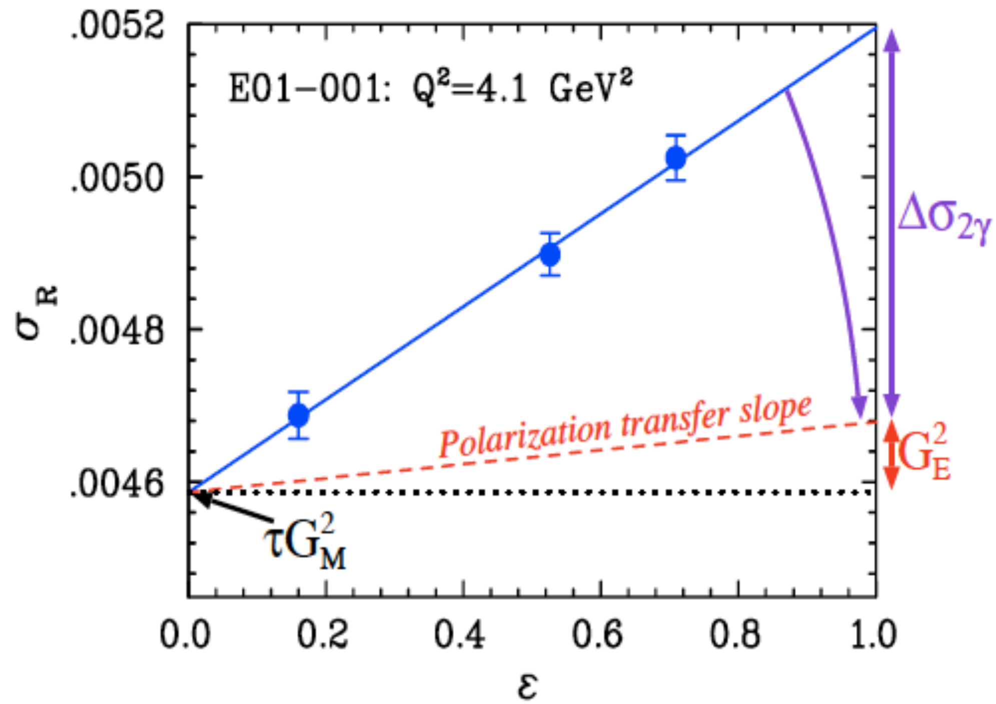


- this E05-017
- proton LT
- global LT
- PT
- solid: fit to LT
- dashed: fit to PT

Effect of two-photon exchange

J. Arrington, P. Blunden, W. Melnitchouk, Prog. Part. Nucl. Phys. 66, 782 (2011)



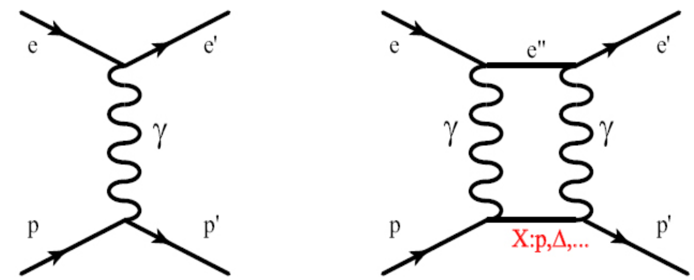


By construction, theorists sought mechanism that affects the "slope" in the Rosenbluth plot (ε-dependence)

At high Q^2 , the contribution of G_E to the cross section is of similar order as the TPE effect (few %)

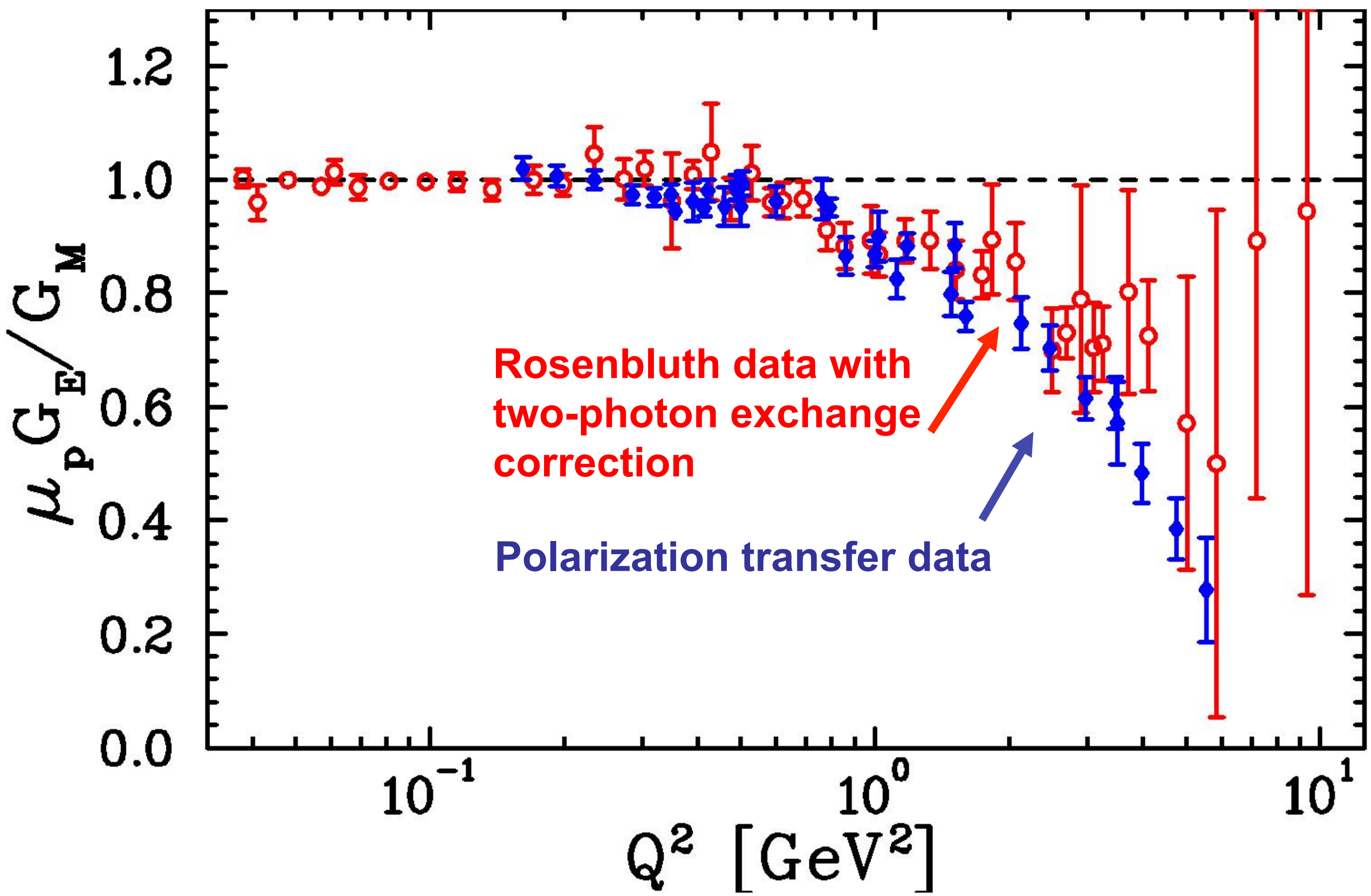
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested

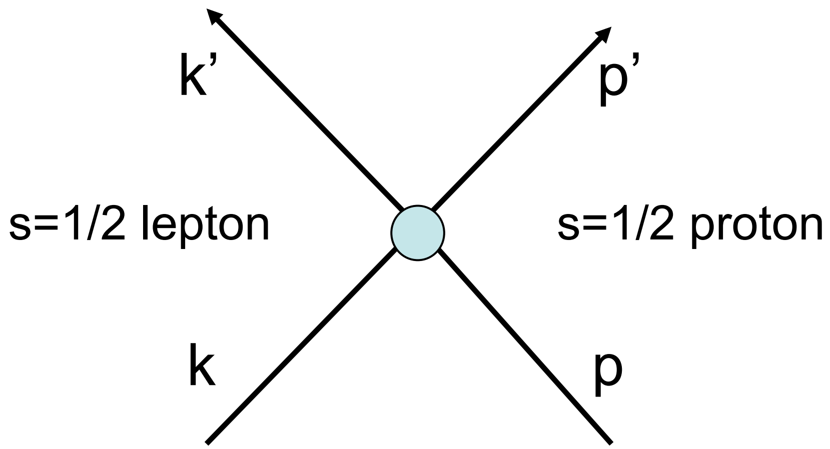


TPE can explain form factor discrepancy

J. Arrington, W. Melnitchouk, J.A. Tjon, Phys. Rev. C 76, 035205 (2007)



Elastic ep scattering beyond OPE



$$P \equiv \frac{p+p'}{2}, \quad K \equiv \frac{k+k'}{2}$$

Kinematical invariants :

$$\begin{aligned} Q^2 &= -(p-p')^2 \\ \nu &= K \cdot P = (s-u)/4 \end{aligned}$$

Next-to Born approximation:

$$T^{non-flip}_{h'\lambda'_N, h\lambda_N} = \frac{e^2}{Q^2} \bar{u}(k',h')\gamma_\mu u(k,h)$$

$$\times \quad \bar{u}(p',\lambda'_N) \left(\tilde{G}_M \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma.K P^\mu}{M^2} \right) u(p,\lambda_N)$$

($m_e = 0$)

The T-matrix still factorizes, however a new response term F_3 is generated by TPE

Born-amplitudes are modified in presence of TPE; modifications ~α^3

$$\begin{aligned} \tilde{G}_M(\nu,Q^2) &= G_M(Q^2) + \delta\tilde{G}_M \\ \tilde{F}_2(\nu,Q^2) &= F_2(Q^2) + \delta\tilde{F}_2 \\ \tilde{F}_3(\nu,Q^2) &= 0 + \delta\tilde{F}_3 \end{aligned}$$

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\tilde{F}_2$$

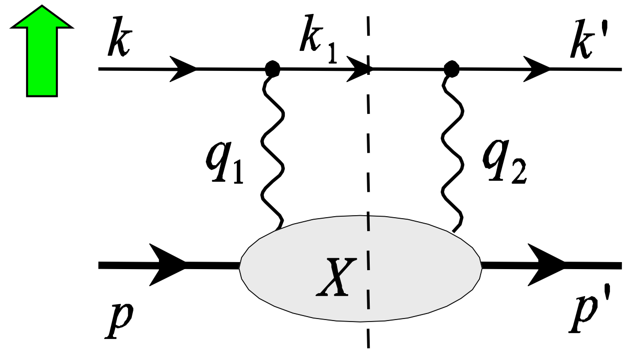
$$\tilde{G}_E(\nu,Q^2) = G_E(Q^2) + \delta\tilde{G}_E$$

New amplitudes are complex!

Inherited from M. Vanderhaeghen

Imaginary part: Single-spin asymmetries

spin of beam OR target
NORMAL to scattering plane



$$s = (k+p)^2$$

on-shell intermediate state ($M_X = W$)

$$A_n = -\frac{1}{(2\pi)^3}\frac{e^2(1-\varepsilon)}{8\,Q^2}\int_{M^2}^{s} dW^2\,\frac{|\vec{k}_1|^2}{4\sqrt{s}}\int d\Omega_{k1}\,\frac{1}{Q_1^2\,Q_2^2}\,\mathcal{I}\left(L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right)$$

E.g. target normal spin asymmetry

$$A_n = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\left\{-G_M\,\mathcal{I}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E\,\mathcal{I}\left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\},$$

⇧**Beam:** PVES at Bates, MAMI and Jlab;
⇧**Target:** (Quasi-)elastic: E05-015: ^{3}He⇧(e,e'), E08-005: ^{3}He⇧(e,e'n)
Deep inelastic: E07-013; HERMES p⇧(e,e')

Inherited from M. Vanderhaeghen

Observables involving real part of TPE

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\frac{G_M^2}{d\sigma_{red}}\left\{R + R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + Y_{2\gamma}\right\}$$

$$P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)}\frac{G_M^2}{d\sigma_{red}}\left\{1 + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon}\varepsilon Y_{2\gamma}\right\}$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}}\left\{R - R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + 2\left(1 - R\frac{2\varepsilon}{1+\varepsilon}\right)Y_{2\gamma}\right\}$$

E04-019 (Two-gamma)

$$d\sigma_{red}/G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R\frac{\varepsilon\Re(\delta\tilde{G}_E)}{\tau G_M} + 2\left(1+\frac{R}{\tau}\right)\varepsilon Y_{2\gamma}$$

e^+/e^- x-section ratio CLAS,VEPP3,OLYMPUS

Rosenbluth non-linearity E05-017

$$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2,\varepsilon))$$

$$\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2,\varepsilon))$$

$$R = G_E / G_M \qquad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}}\frac{\Re(\tilde{F}_3(Q^2,\varepsilon))}{G_M}$$

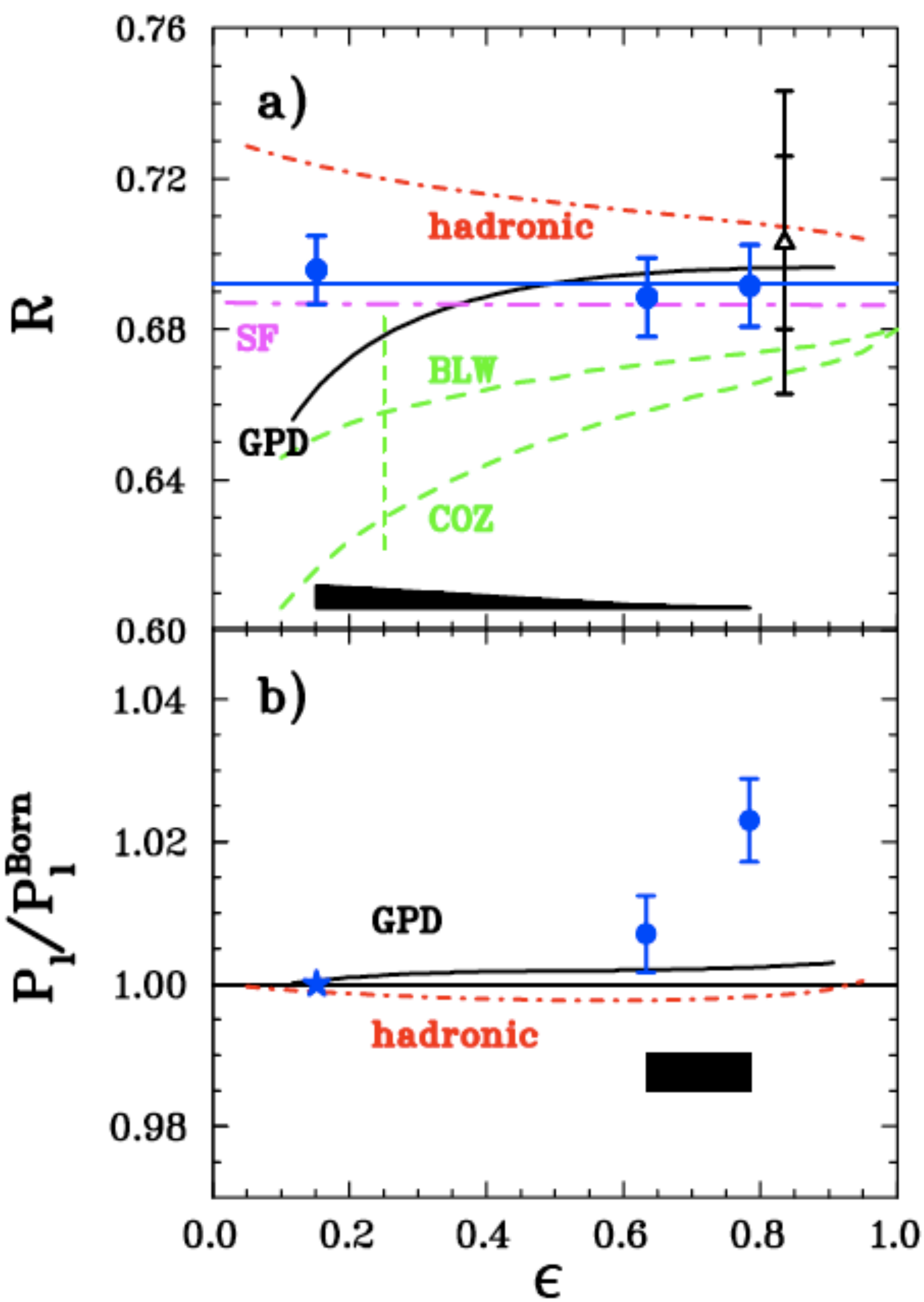
Born Approximation | **Beyond Born Approximation**

P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)

Slide idea: L. Pentchev

Jefferson Lab E04-019 (Two-gamma)



Jlab – Hall C
Q^2 = 2.5 (GeV/c)^2

G_E/G_M from P_t/P_l constant vs. ε

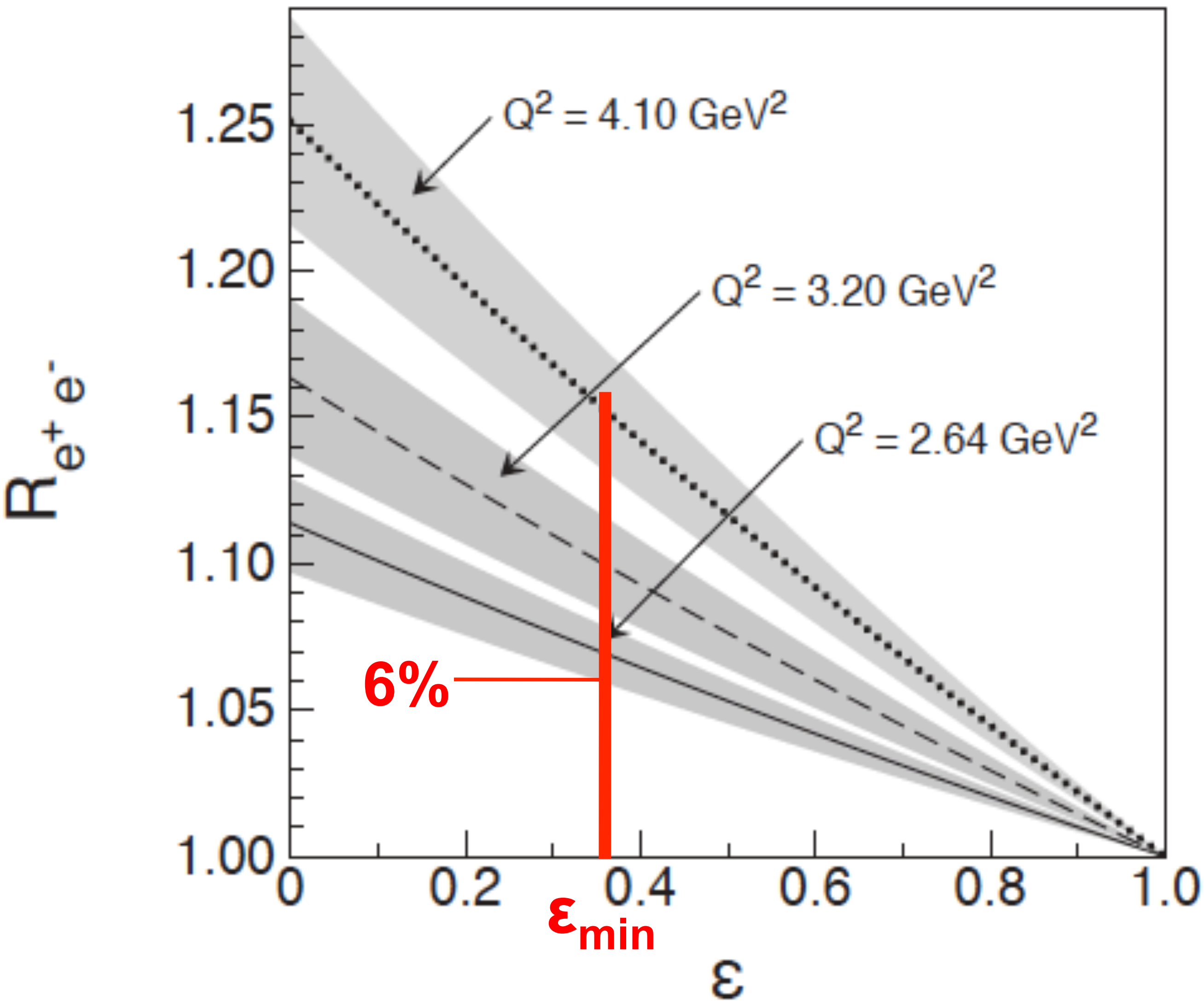
➔ **no effect in P_t/P_l**
➔ **some effect in P_l**

Expect larger effect in e+/e-!

M. Meziane *et al.*, hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

Empirical extraction of TPE amplitudes

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47, 77 (2011)



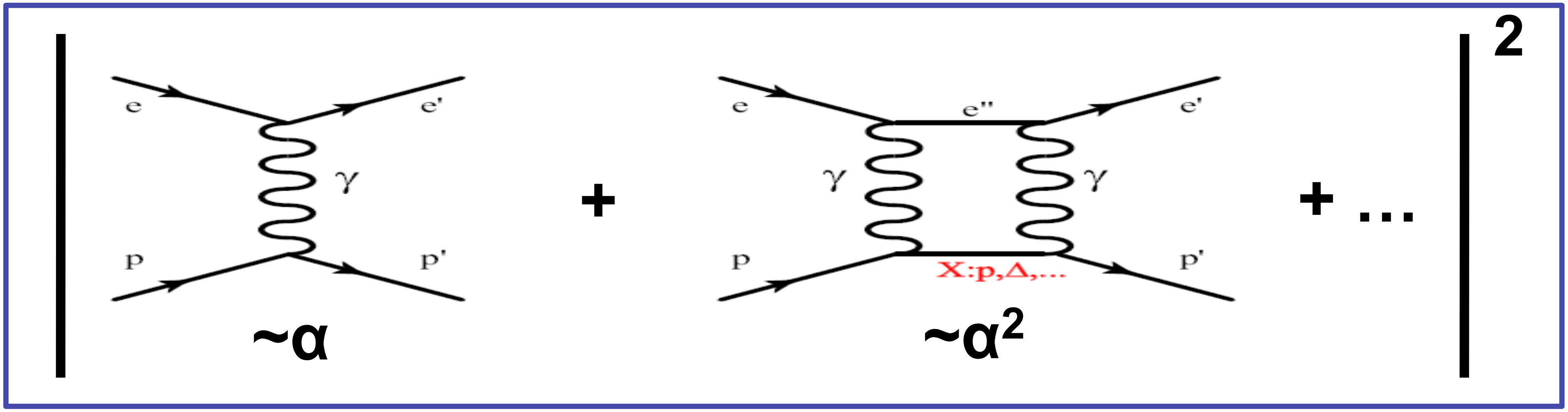
grows with Q^2!

Expect ~6% effect for OLYMPUS@2.0GeV

ε_{min}>0.35, Q^2<2.2 (GeV/c)^2

OLYMPUS

Lepton-proton elastic scattering



- Interference term depends on lepton charge sign (C-odd)

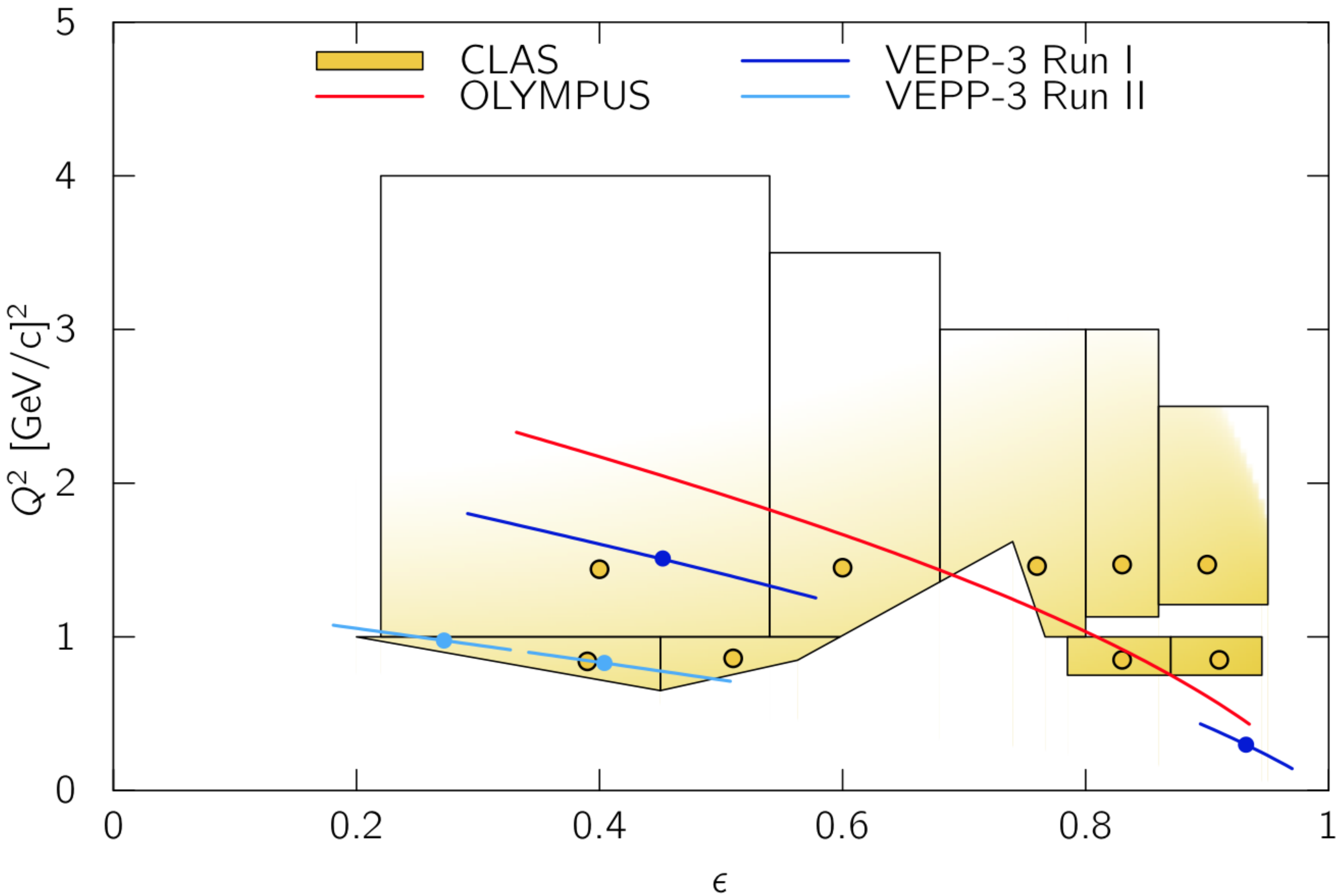
$$\sigma_{e^{\pm}p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}^{\dagger}_{1\gamma}\mathcal{M}_{2\gamma}\} + \cdots$$

- e^+/e^- ratio deviates from unity by two-photon contribution

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}^{\dagger}_{1\gamma}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Comparison of e^+/e^- experiments

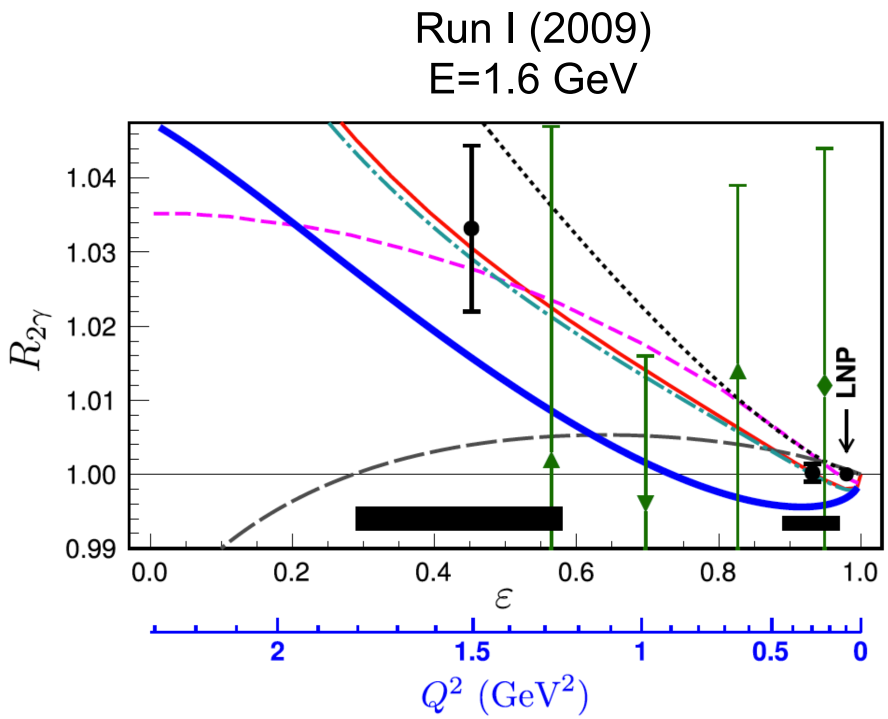
- **VEPP-3 @ Novosibirsk: E_{beam} = 1.6, 1.0 (and 0.6) GeV**
- **CLAS @ JLAB : E_{beam} = 0.5 – 4.0 GeV continuous**
- **OLYMPUS @ DESY: E_{beam} = 2.0 GeV**

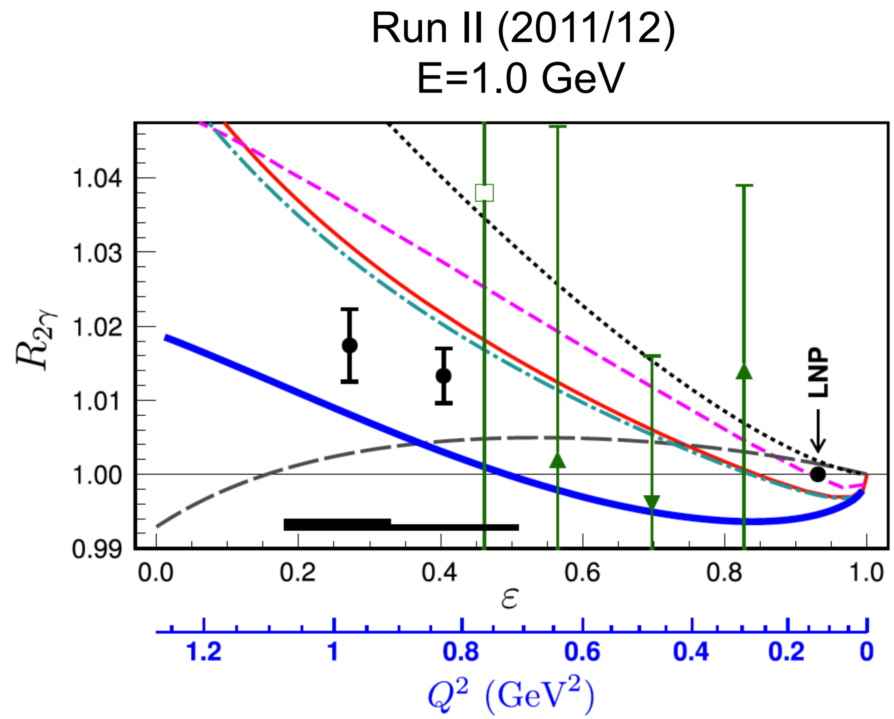


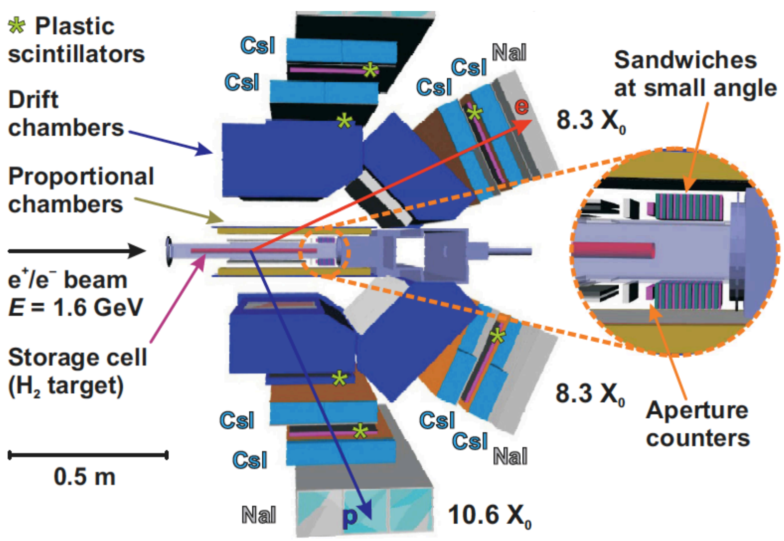
Comparison of e^+/e^- experiments

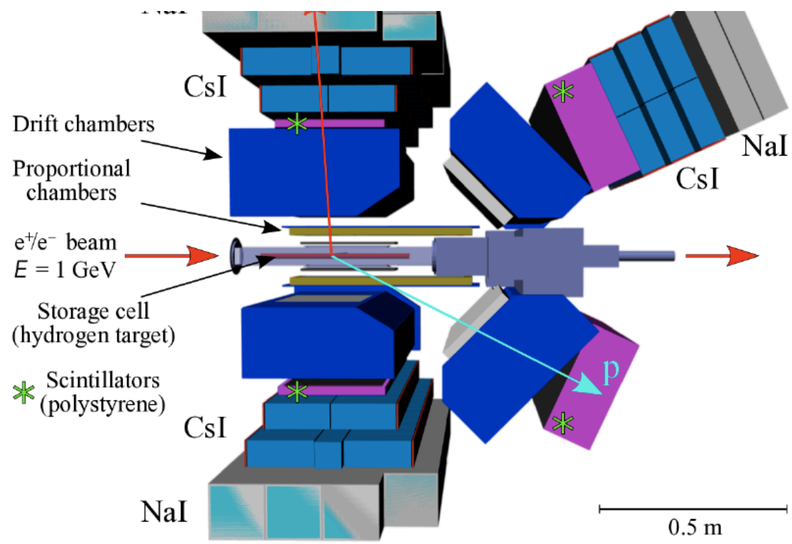
	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^\pm$ beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	24 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy of scattered $e^\pm$	EM-calorimeter	mag. analysis	mag. analysis
proton PID	$\Delta E/E$, TOF	mag. analysis, TOF	mag. analysis, TOF
e^+/e^- detector acceptance	identical	big difference	big difference
luminosity	1.0×10^{32}	2.0×10^{33}	2.5×10^{32}
beam type	storage ring	storage ring	secondary beam
target type	internal H target	internal H target	liquid H target
data taken	2009, 2011-12	2012	2011
published	2015	2017	2015

TPE experiments: Novosibirsk/VEPP-3



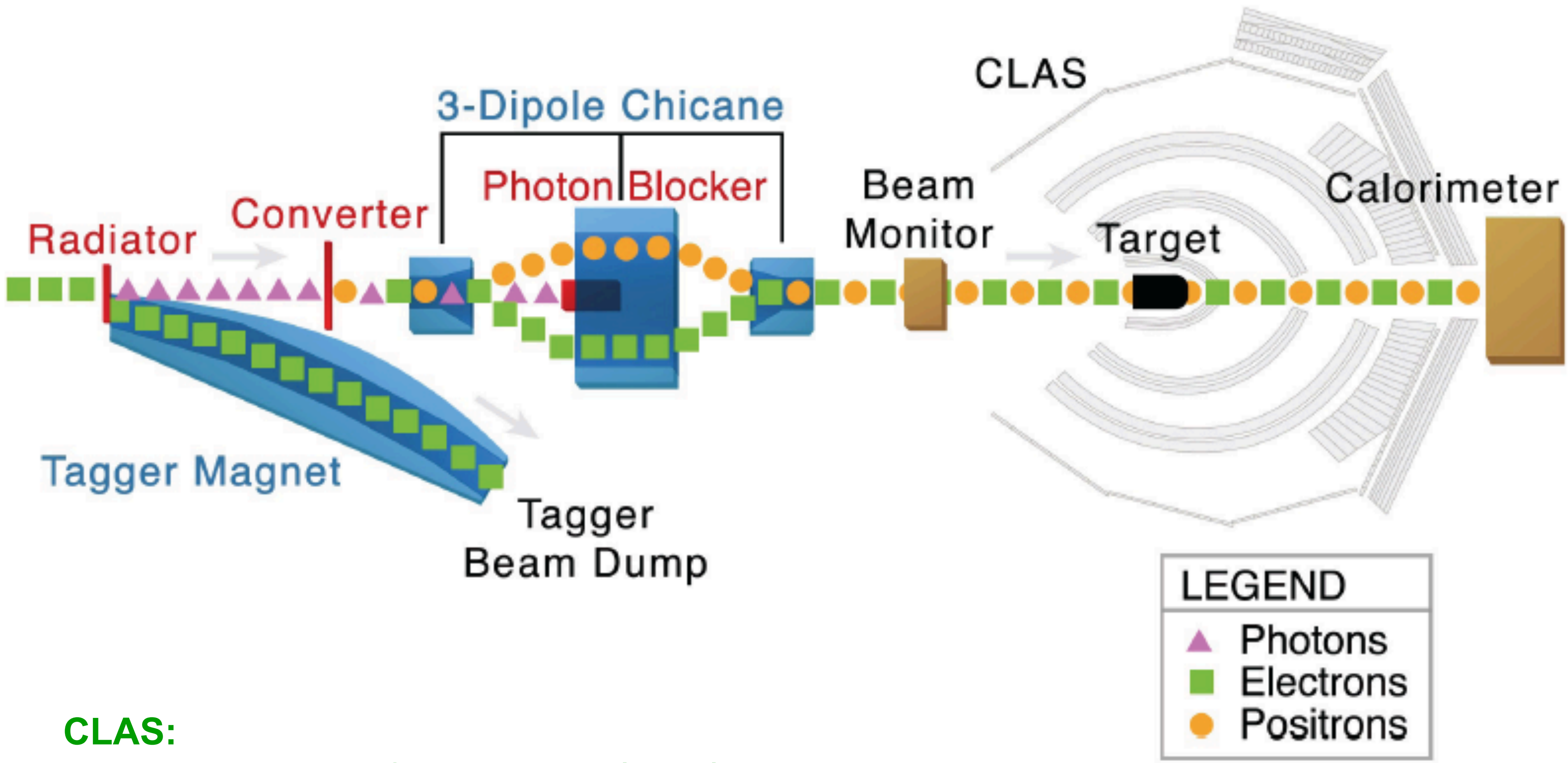






I.A. Rachek *et al.*, PRL 114, 062005 (2015)

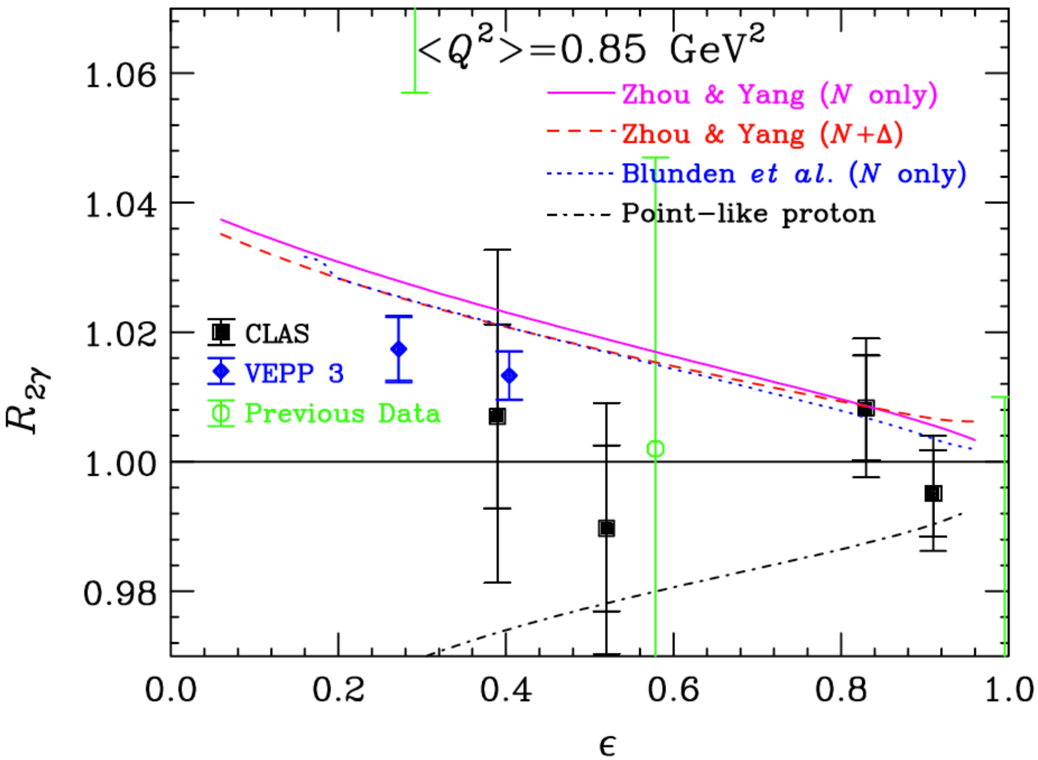
TPE experiments: CLAS (E04-116)

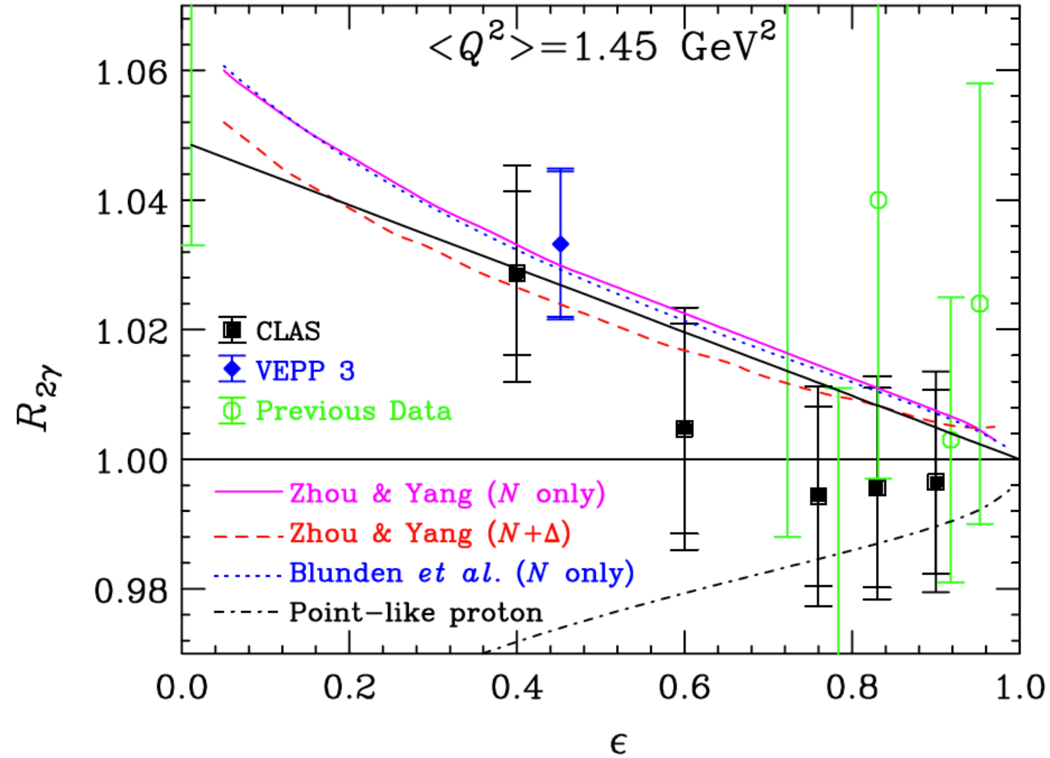


CLAS:
D. Rimal *et al.*, PRC 95, 065201 (2017)
D. Adikaram *et al.*, PRL 114, 062003 (2015)

TPE experiments: CLAS (E04-116)

ε dependence





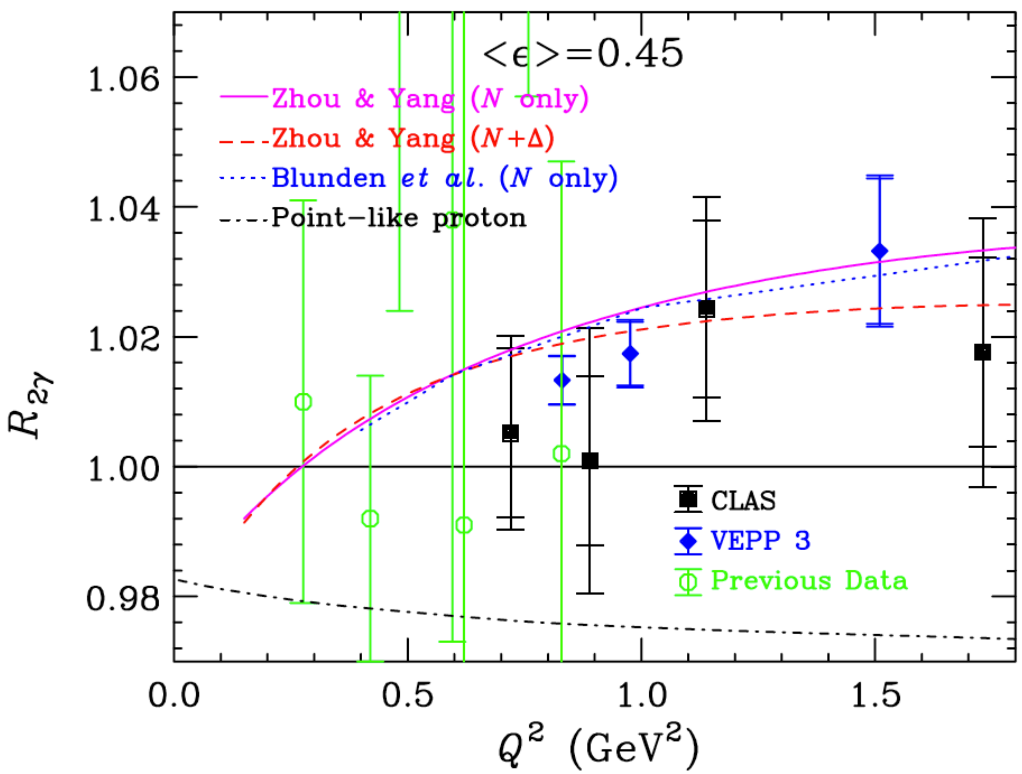
CLAS:
D. Rimal *et al.*, PRC 95, 065201 (2017)
D. Adikaram *et al.*, PRL 114, 062003 (2015)

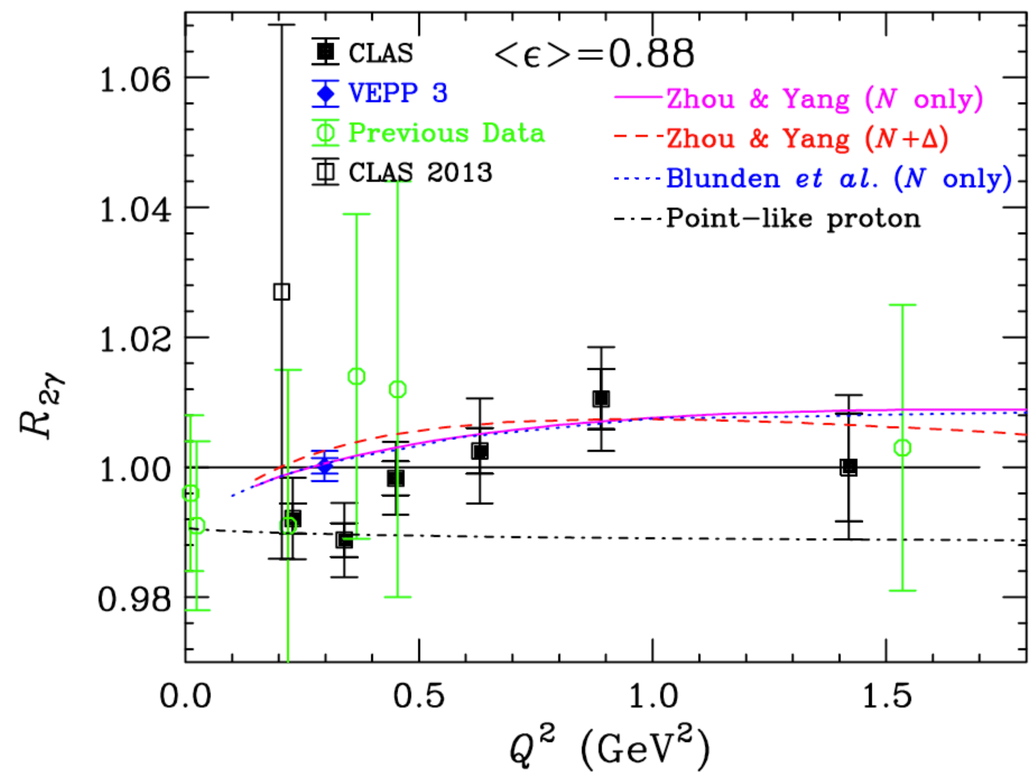
VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

CLAS result consistent with “standard” TPE prescription
… however, limited precision

TPE experiments: CLAS (E04-116)

Q^2 dependence



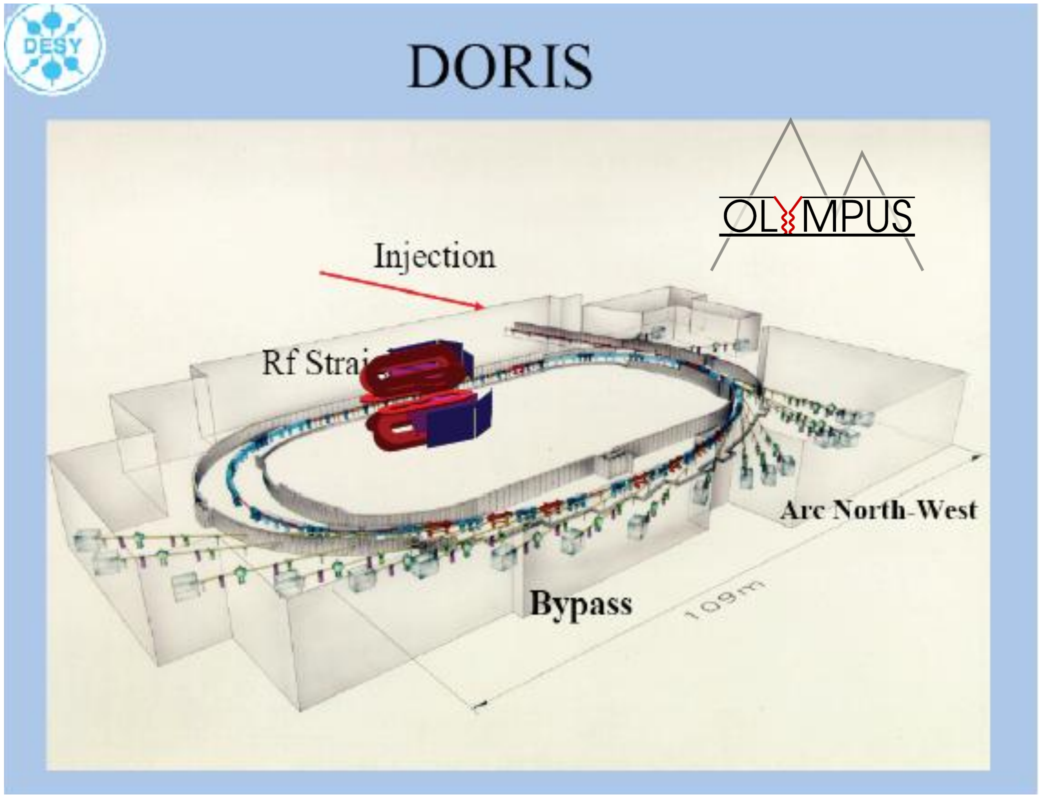


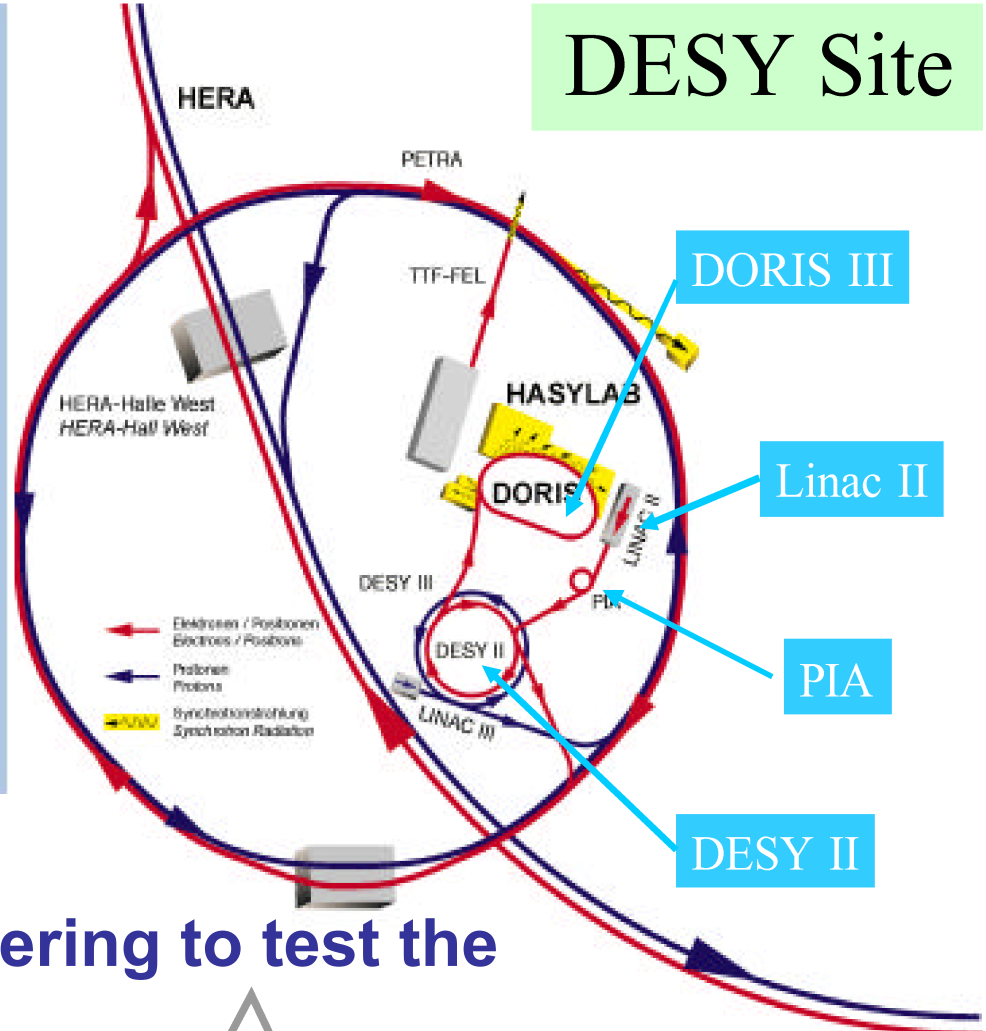
CLAS:
D. Rimal *et al.*, PRC 95, 065201 (2017)
D. Adikaram *et al.*, PRL 114, 062003 (2015)

VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

CLAS result consistent with "standard" TPE prescription
… however, limited precision

OLYMPUS @ DORIS/DESY





pOsitron-proton and

eLectron-proton elastic scattering to test the

hYpothesis of

Multi-

Photon exchange

Using

DoriS

OLYMPUS collaboration

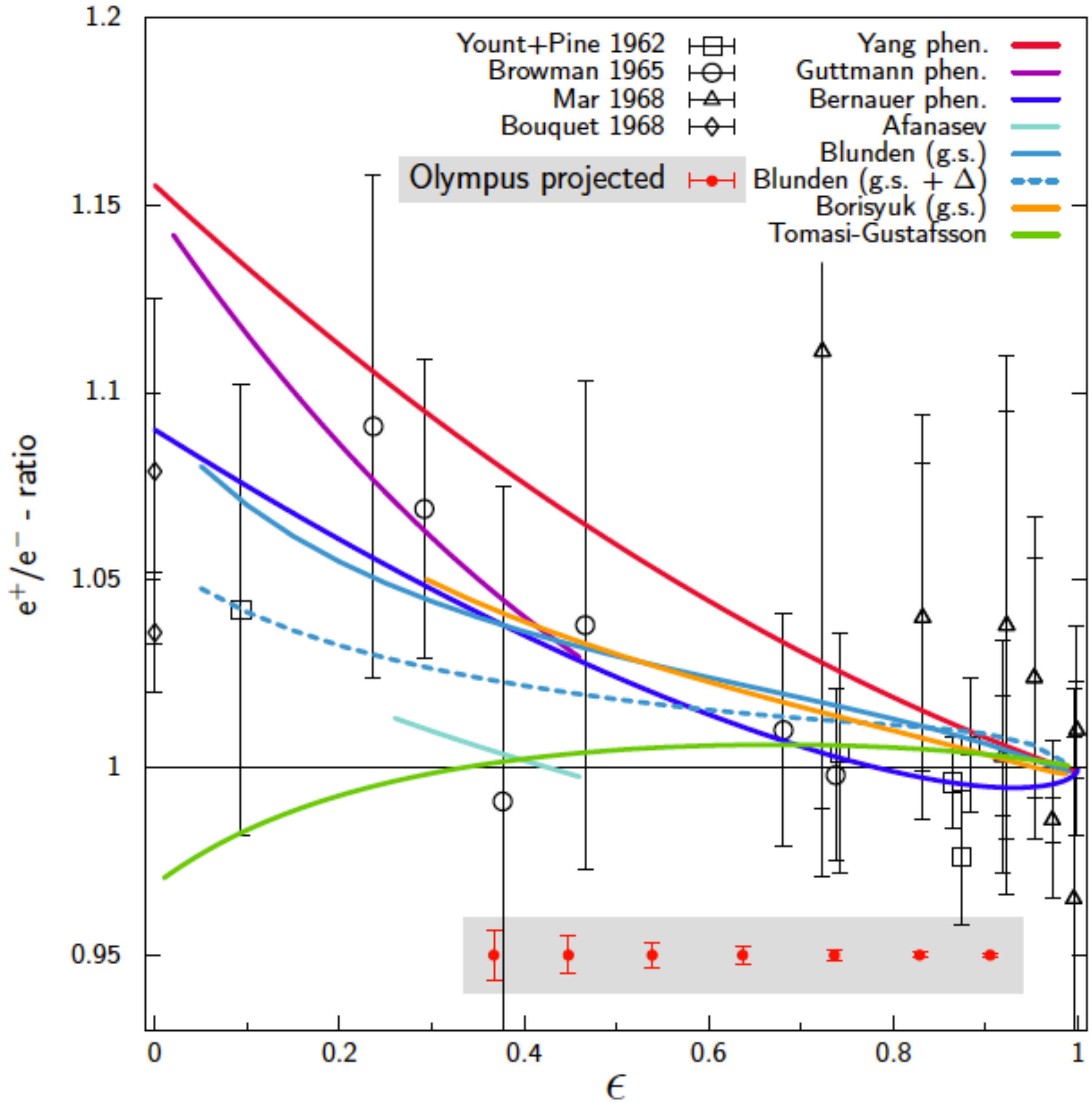
~50 physicists from 13 institutions in 6 countries

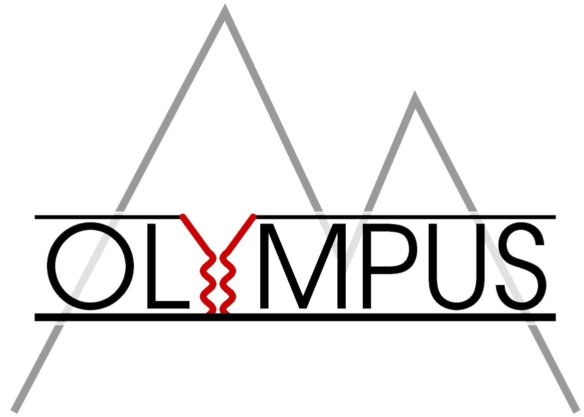
Elected spokesmen / deputy:	R. Milner / R. Beck	(2009–2011)
	M.K. / A. Winnebeck	(2011–2013)
	D. Hasell / U. Schneekloth	(2013–)

PhDs: O. Ates, A. Schmidt, R. Russell, B. Henderson, L. Ice, C. O'Connor, D. Khaneft

- **Arizona State University:** TOF support, particle identification, magnetic shielding
- **DESY:** Modifications to DORIS accelerator and beamline, toroid support, infrastructure, installation
- **Hampton University:** GEM luminosity monitor
- **INFN Bari:** GEM electronics
- **INFN Ferrara:** Target
- **INFN Rome:** GEM electronics
- **MIT:** BLAST spectrometer, wire chambers, tracking upgrade, target and vacuum system, transportation to DESY, simulations, slow control, analysis framework
- **Petersburg Nuclear Physics Institute:** MWPC luminosity monitor
- **University of Bonn:** Trigger, data acquisition, and online monitor
- **University of Mainz:** Trigger, DAQ, Symmetric Moller monitor
- **University of Glasgow**: TOF scintillators
- **University of New Hampshire:** TOF scintillators
- **A. Alikhanyan National Laboratory (AANL), Yerevan:** TOF scintillators

Projected results for OLYMPUS





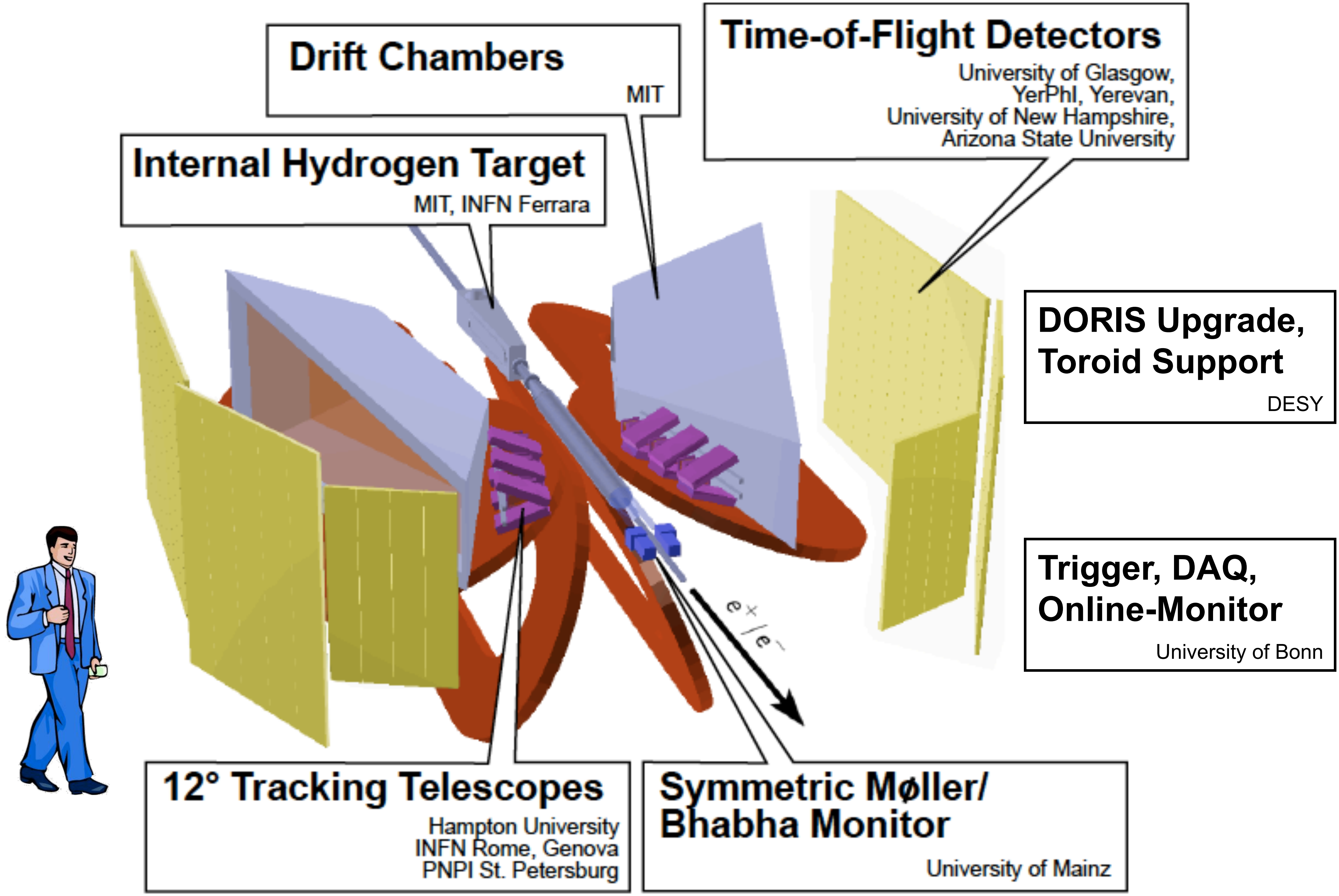
Data from 1960's

Many theoretical predictions with little constraint

OLYMPUS:
- **E= 2.0 GeV**
- **$0.4 < Q^2/(\text{GeV}/c)^2 < 2.2$**
- **Acquire 3.6 fb^{-1} for <1% projected uncertainties**

Data taking completed in 2012

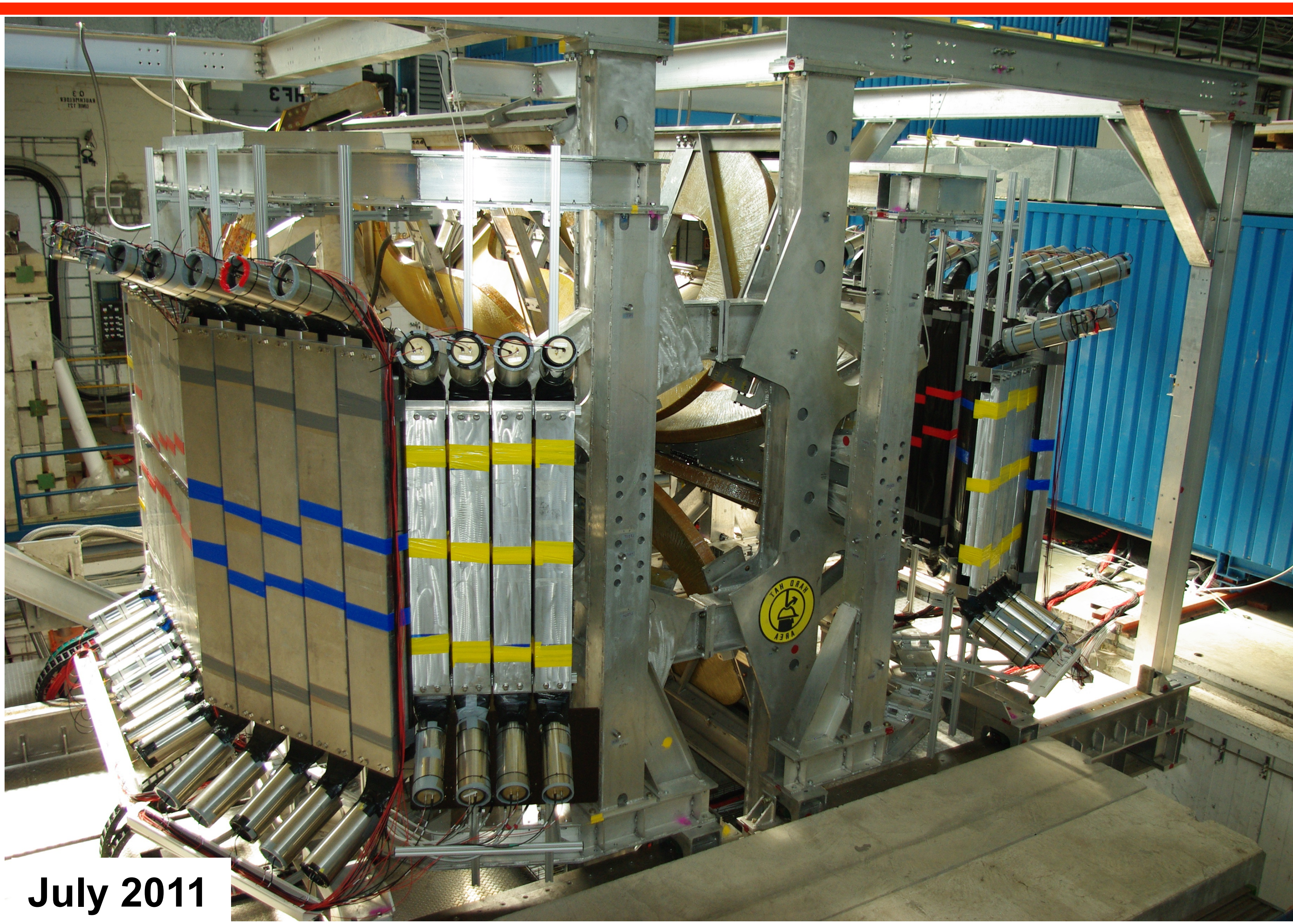
The designed OLYMPUS detector



based on a figure by R. Russell

The realized OLYMPUS detector

OLYMPUS



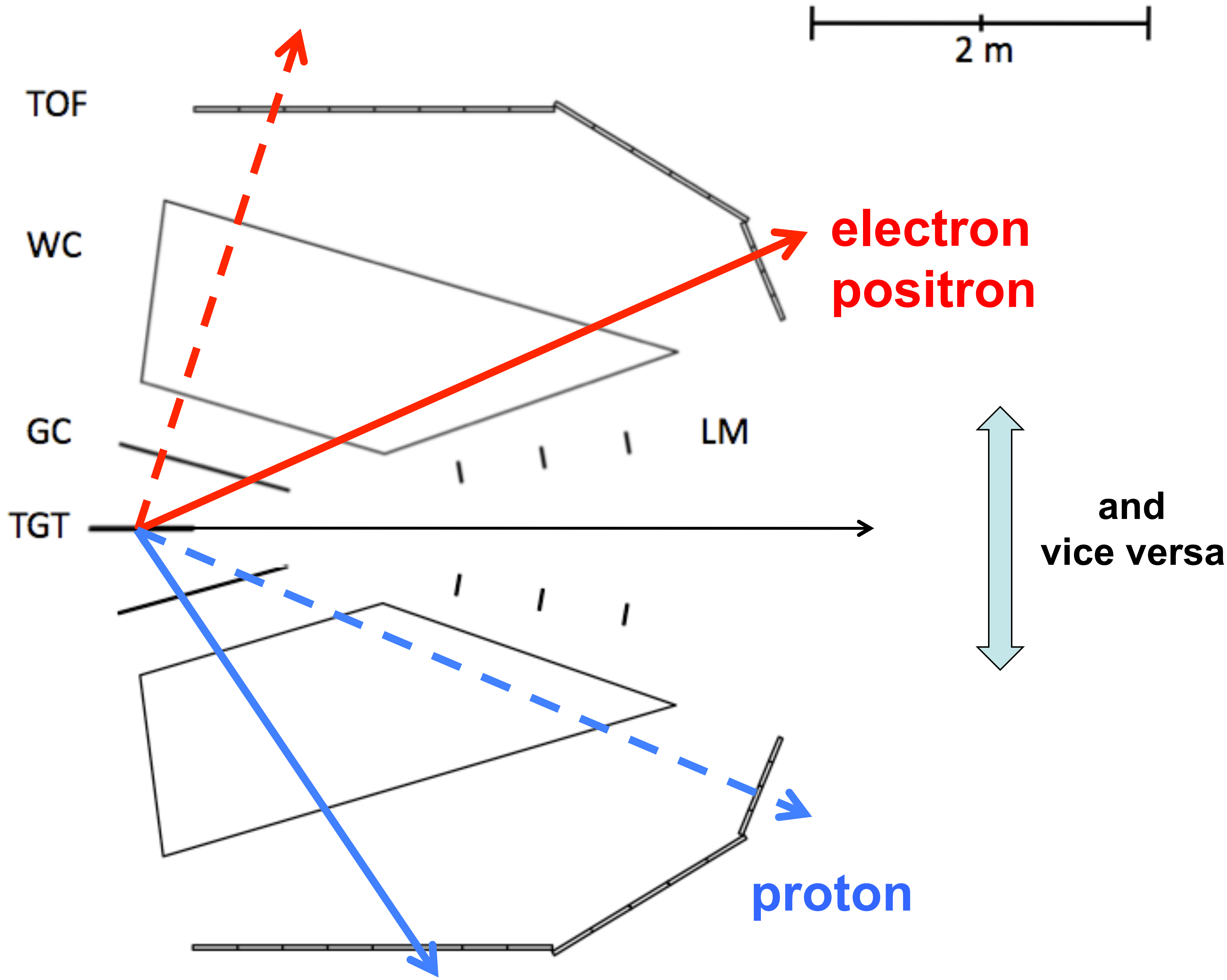
July 2011

Apparatus: ***"The OLYMPUS Experiment"*, R. Milner *et al.*, NIMA 741, 1 (2014)**

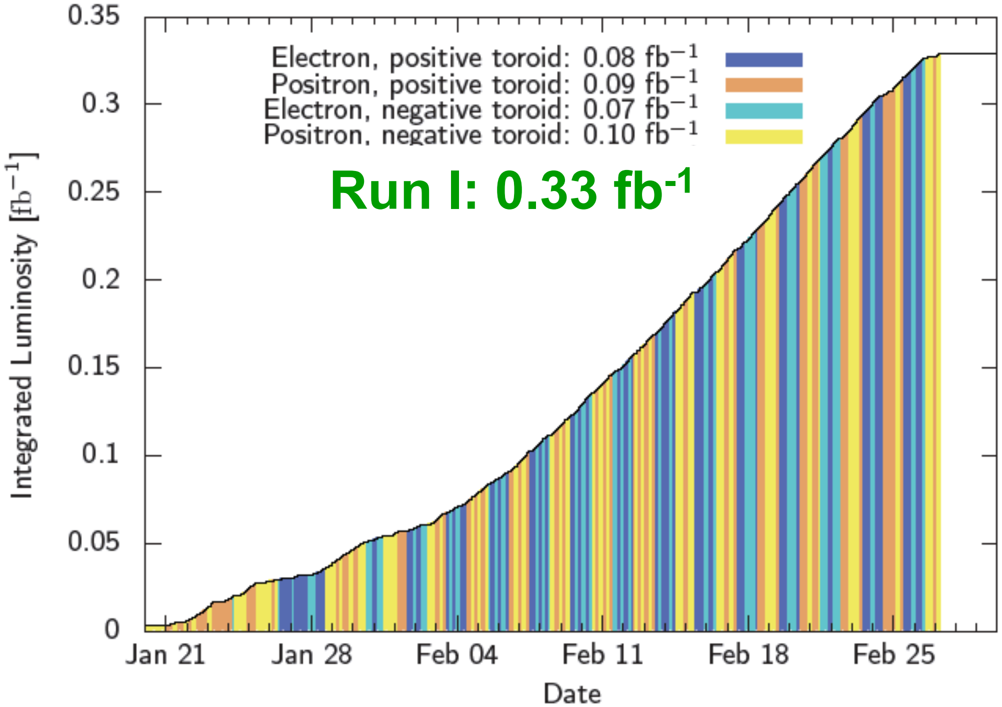
Target: ***"The OLYMPUS internal hydrogen target"*, J.C. Bernauer, NIMA 755, 20 (2014)**

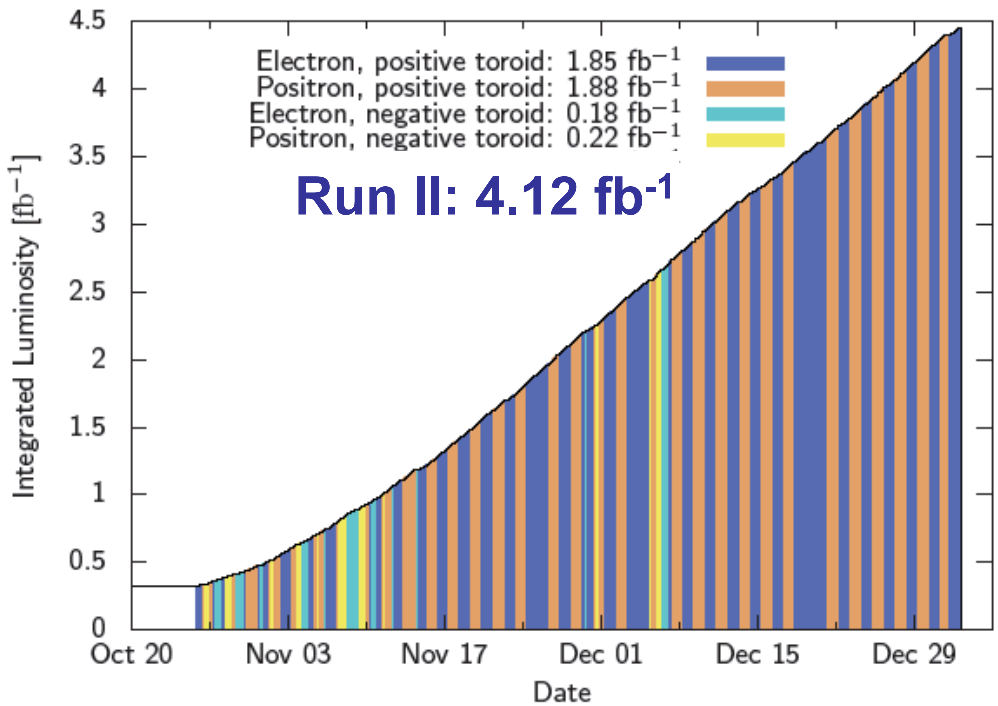
Magnet: ***"Measurement and tricubic interpolation of the magnetic field for the OLYMPUS experiment"*, J.C. Bernauer *et al.*, NIMA 823, 9 (2016)**

OLYMPUS kinematics at 2.0 GeV



Timeline of OLYMPUS





- 2007 Letter of Intent
- 2008 Proposal
- 2009 Technical review
- 2010 Approval and funding
- Summer 2010 BLAST transfer
- Spring 2011 Target test run
- Summer 2011 Detector installed
- Fall 2011 Commissioning

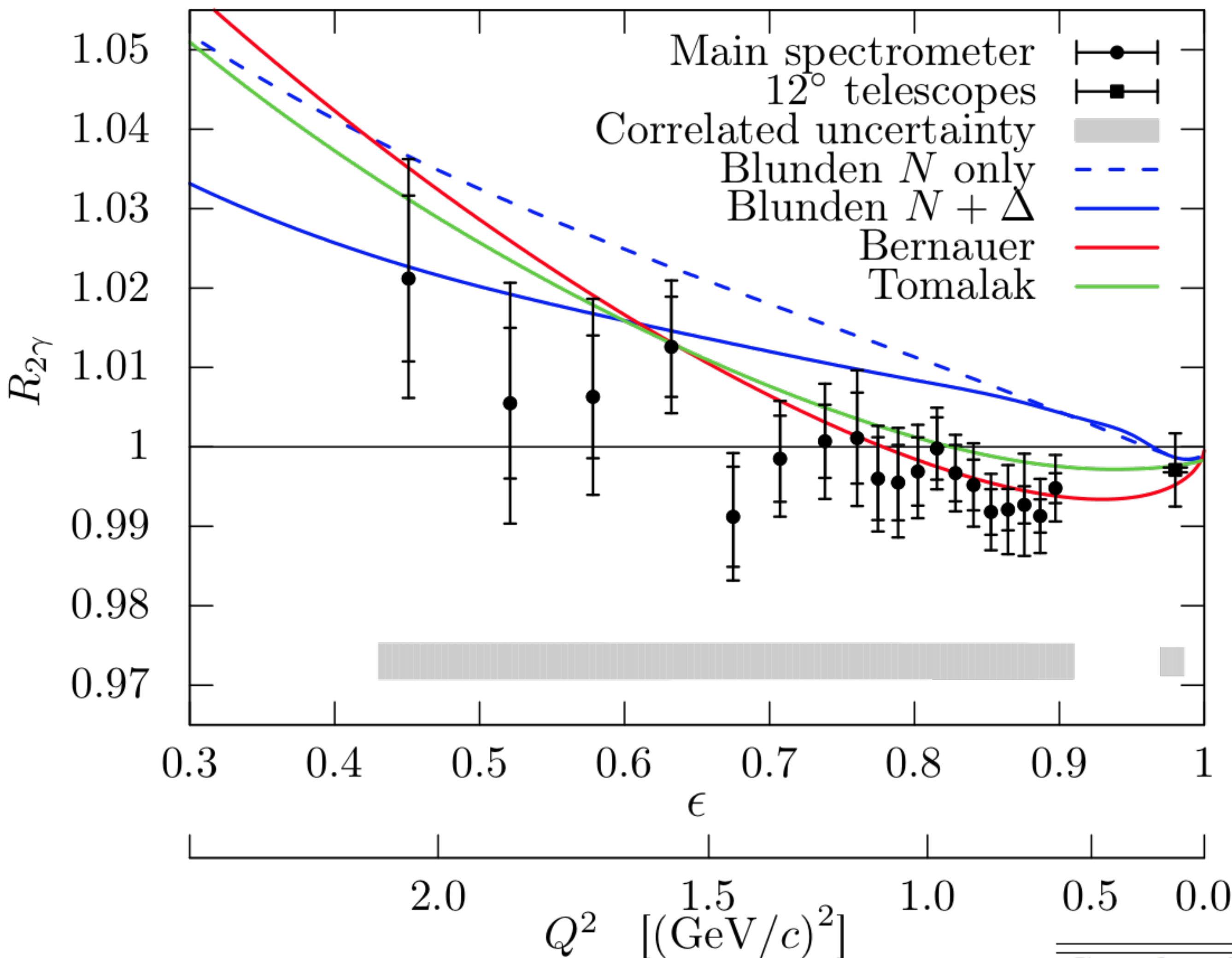
First run Jan 30 – Feb 27, 2012
… acquired < 0.3 fb^{-1}

- Summer 2012 Repairs and upgrades

Second run Oct 24, 2012 – Jan 2, 2013
… acquired > 4.0 fb^{-1}

- Smooth performance of machine, target, detector
- Spring 2013 Survey & field mapping
- Analysis progressing – framework, calibrations, tracking, simulations
- **Results released in November 2016**

Result for hard two-photon exchange



- **Mo-Tsai to all orders**
- **Results based on 3.1 fb^{-1}, statistics 0.2 – 1%**

Hard TPE is small !

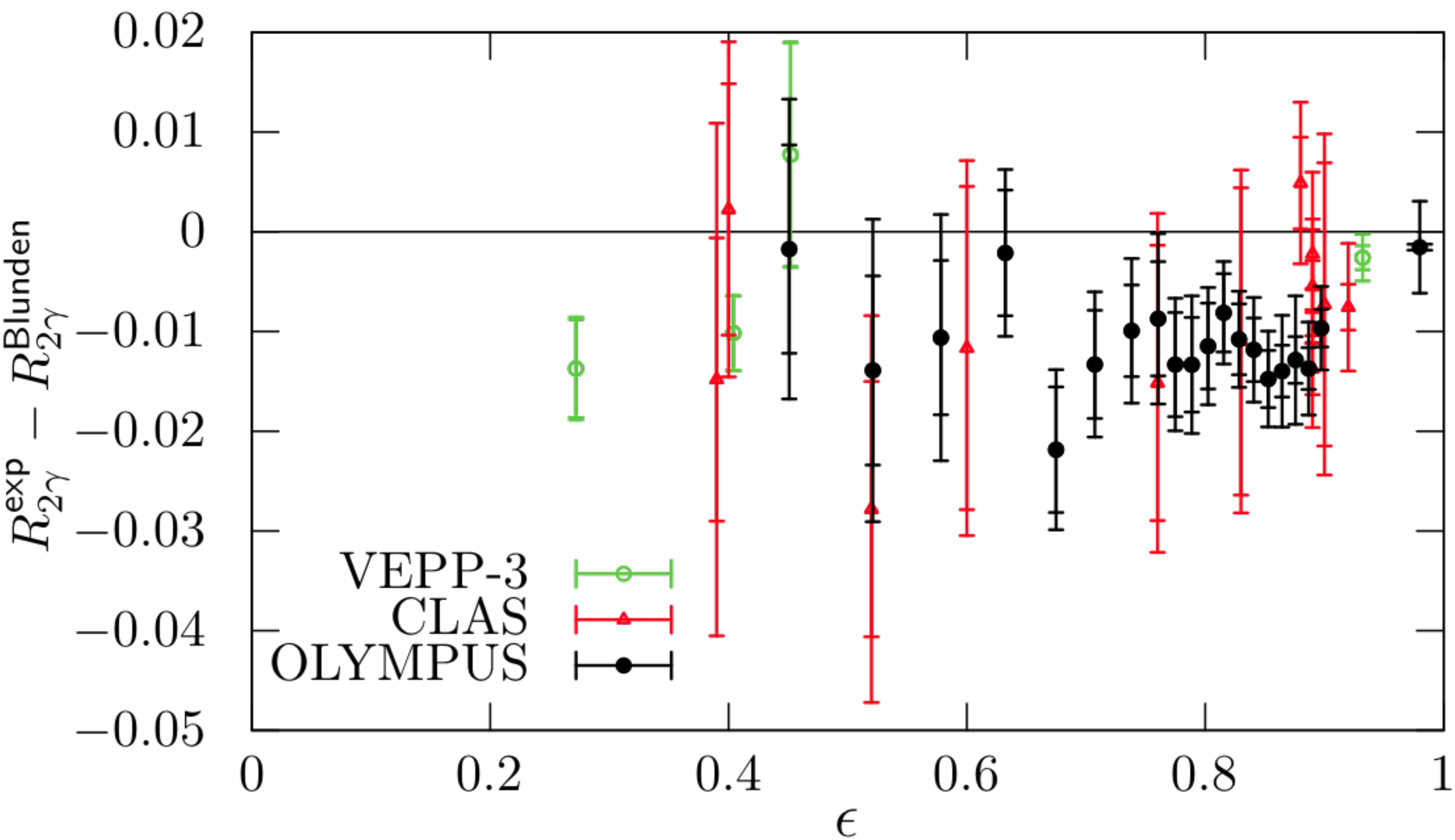
- **Below Hadronic Model by Blunden at low Q^2**
- **Good agreement with phenomenology**

Data needed at higher $Q^2 > 2.5\ (GeV/c)^2$ where TPE effects are expected to be larger

Correlated contributions	Uncertainty in $R_{2\gamma}$
Beam energy	0.04–0.13%
MIE luminosity	0.36%
Beam and detector geometry	0.25%
Uncorrelated contributions	
Tracking efficiency	0.20%
Elastic selection and background subtraction	0.25–1.17%

B.S. Henderson *et al.*, PRL 118, 092501 (2017)

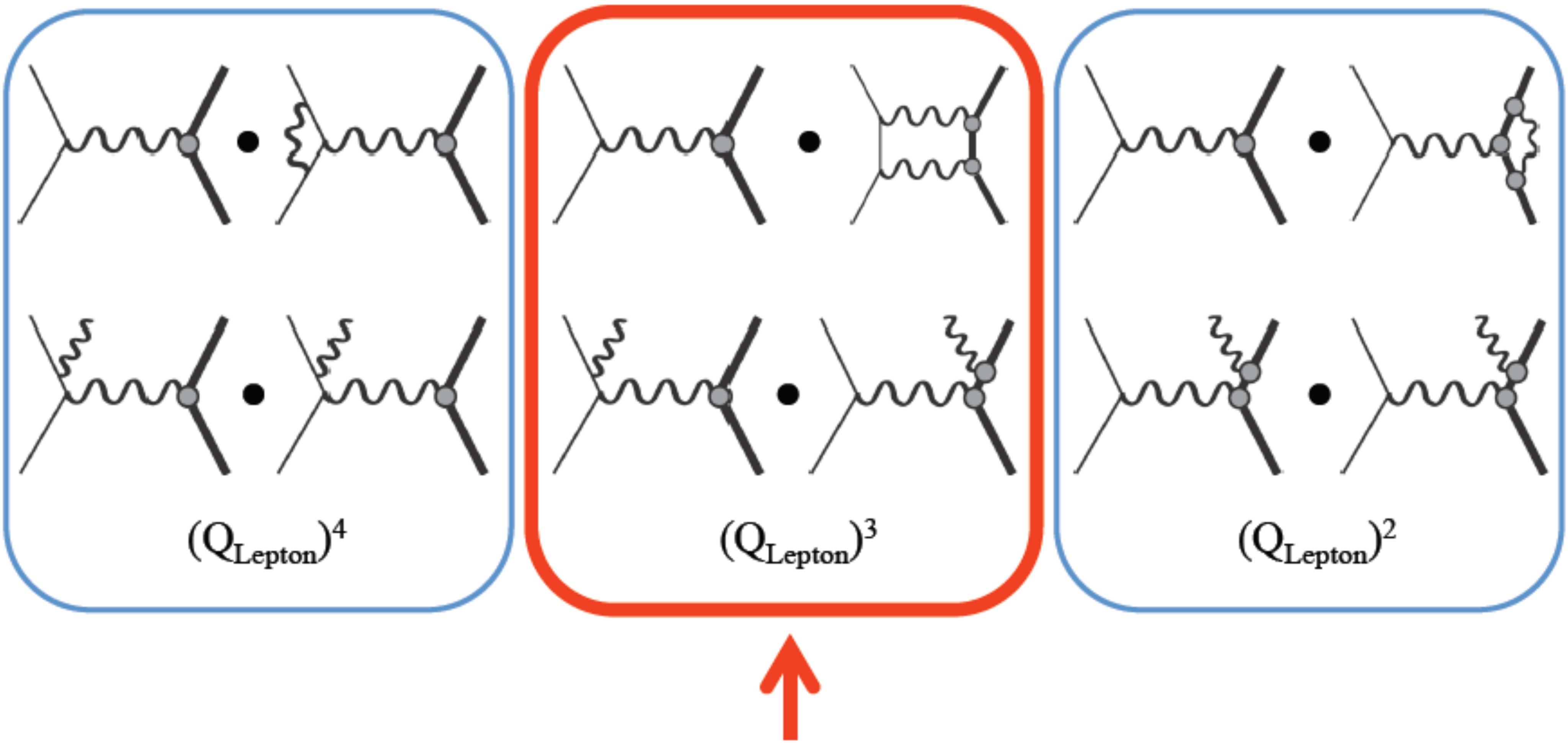
Comparison with VEPP-3 and CLAS



- **OLYMPUS, VEPP-3 and CLAS all in agreement**
- **Hard TPE observed by VEPP-3 and OLYMPUS below Blunden**
- **Limited precision for CLAS**

Radiative corrections of order α^3

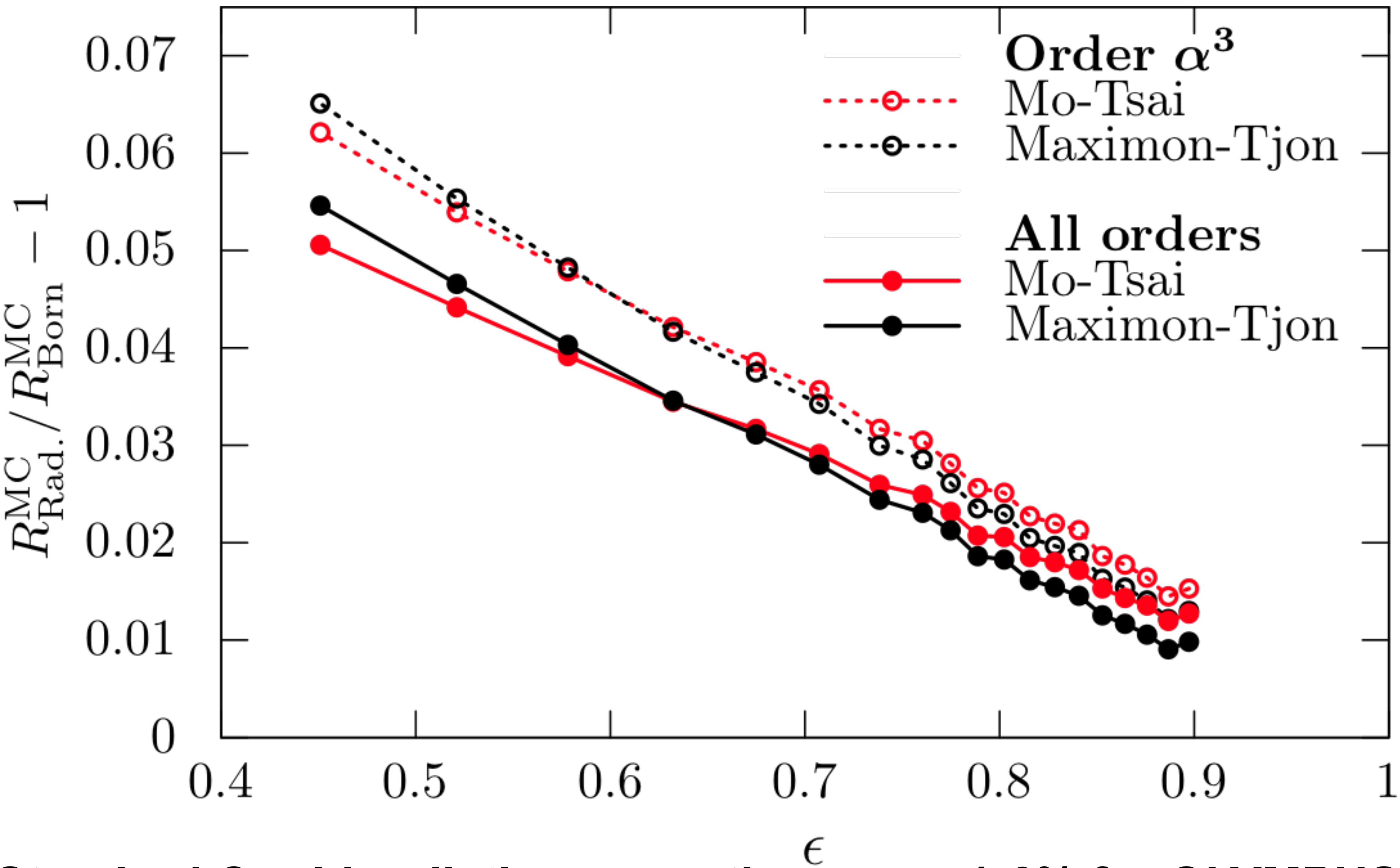
- **Use MC framework to accurately implement all 'standard' RC and to extract effect from hard TPE**
- **Ensure consistency between different experiments**



Changes sign with lepton sign

A. Schmidt, R. Russell, J. Bernauer (MIT)

MIT radiative generator



- Standard C-odd radiative corrections are ~1-6% for OLYMPUS
- Variation due to higher orders at ~1% level

B.S. Henderson *et al.*, PRL 118, 092501 (2017) [arXiv:1611.04685v2]

Summary

- The limits of OPE have been reached with the achieved precision
  - ➔ Large discrepancy between unpolarized and polarized data
  - ➔ Nucleon elastic form factors, particularly G_E^p under doubt
- The TPE hypothesis is suited to remove form factor discrepancy, however calculations of TPE are model-dependent
- New observables: ε dependence of polarization transfer, ε-nonlinearity of cross sections, single-spin asymmetries, e^+/e^- comparisons
- Positron/electron comparisons to test TPE: VEPP-3, CLAS, OLYMPUS
- OLYMPUS: Hard TPE found to be
  - ➔ consistent with other TPE experiments but more precise
  - ➔ smaller than expected by standard hadronic theory at low Q^2
  - ➔ consistent with phenomenology at $Q^2 < 2.5$ (GeV/c)^2
- Need to improve theoretical precision for radiative corrections !
- TPE is to be tested at higher $Q^2 > 2.5$ (GeV/c)^2 with future experiments (e.g. with positron source at CEBAF or extracted beams at DESY)
- Broader Impact:
  - ➔ gamma-Z box in PVES; TPE effects in eA and inelastic scattering;
  - ➔ Proton radius puzzle: elastic $\{\mu,e\}^{\pm}p$ scattering with MUSE@PSI

Outlook

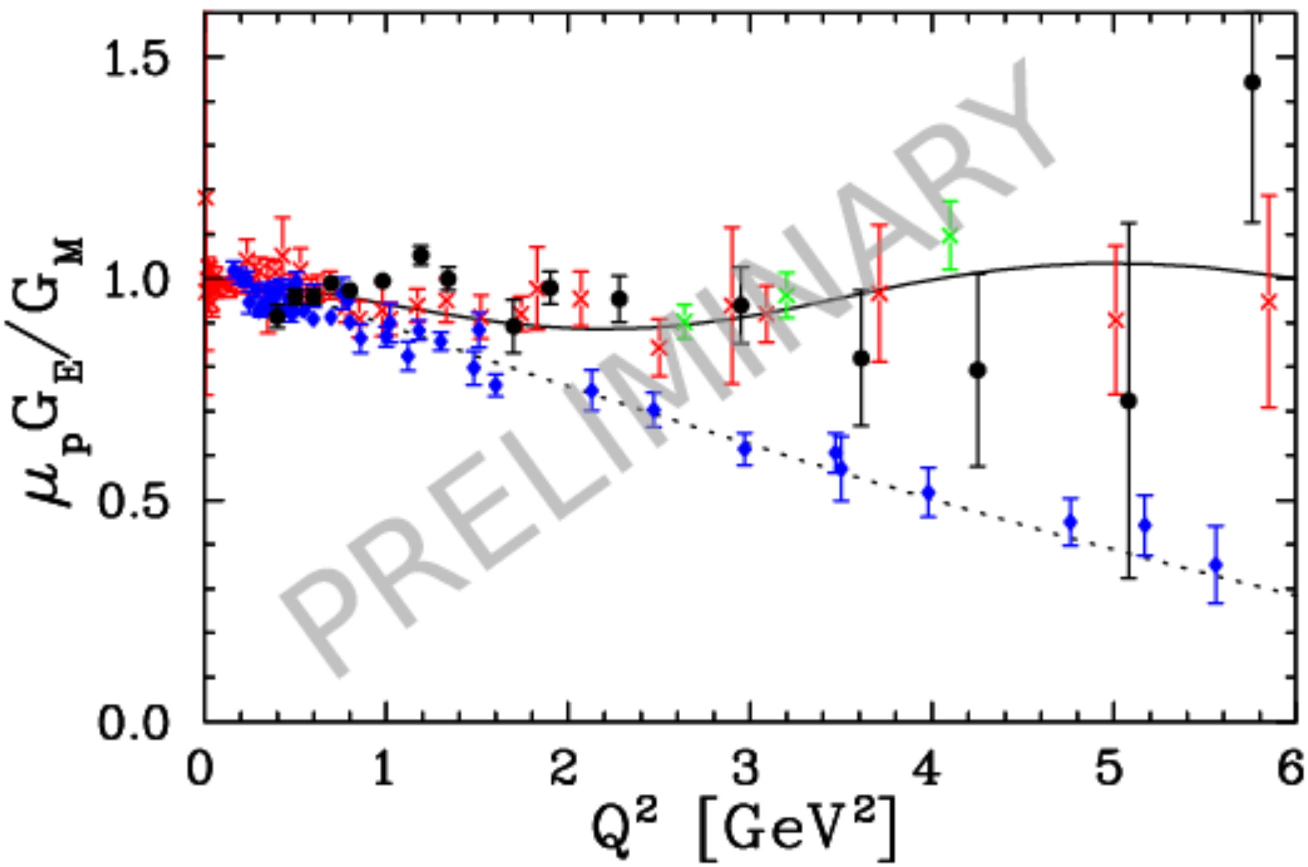
Upcoming Workshops:

- **Hadronic Physics with Lepton and Hadron Beams, Jlab, Sep. 5-8, 2017**
  https://www.jlab.org/conferences/hadrons2017/index.html
- **JPOS2017, JLab, Sep. 12-15, 2017**
  https://www.jlab.org/conferences/JPos2017/
- **EW Box, Amherst, MA, Sep 28-30, 2017**
  http://www.physics.umass.edu/acfi/seminars-and-workshops/the-electroweak-box

Backup

PRELIMINARY RESULTS

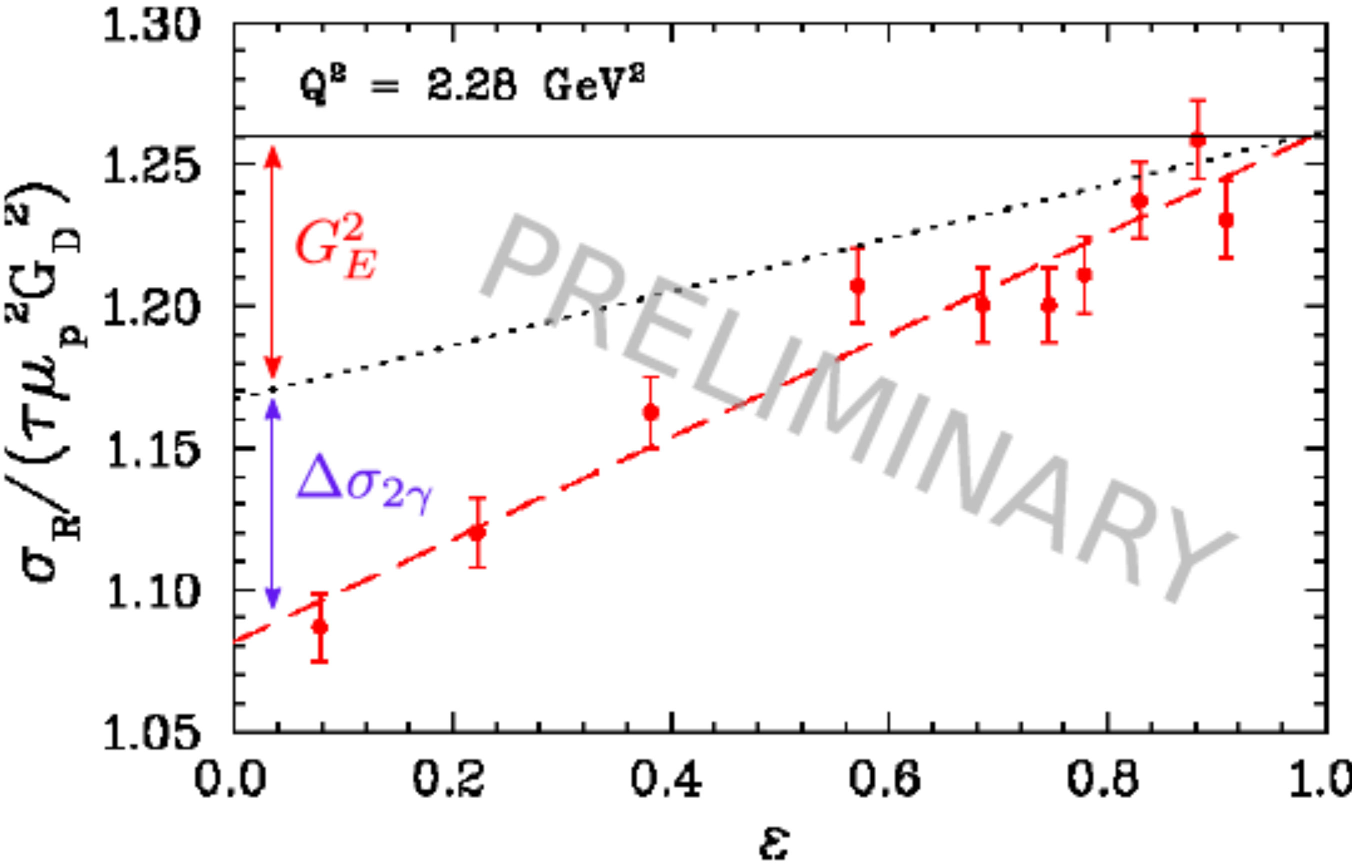
- $\mu_p G_E/G_M$ extraction:
  - from analysis that focused on low Q^2 settings
- expected uncertainty reduction:
  - slope by factor of 2 everywhere
  - point-to-point by factor 1.3 at $Q^2 < 2$ and by 1.5 above



- this E05-017
- proton LT
- global LT
- PT
- solid: fit to LT
- dashed: fit to PT

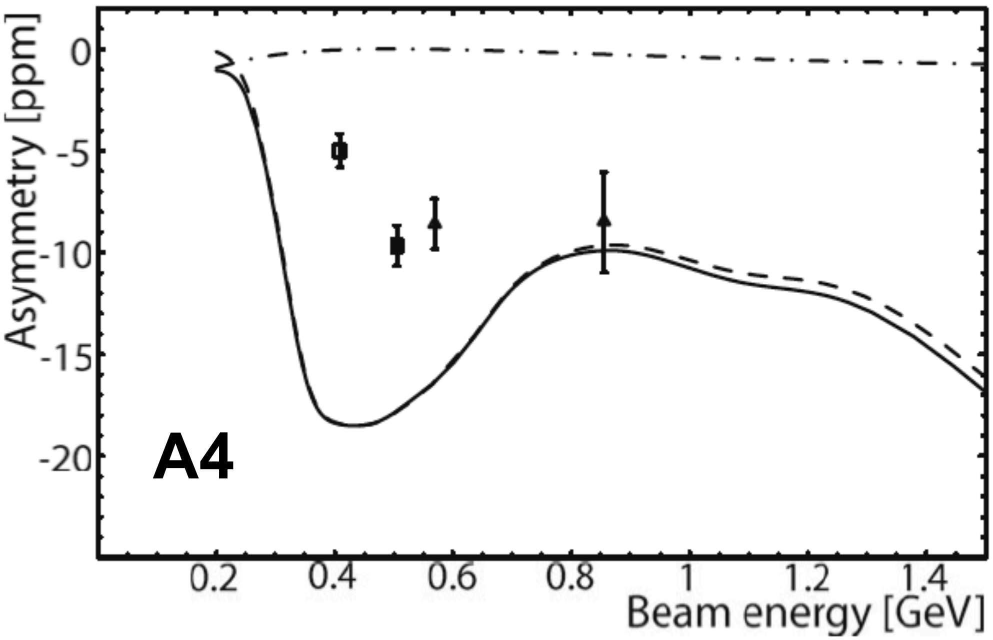
PRELIMINARY RESULTS

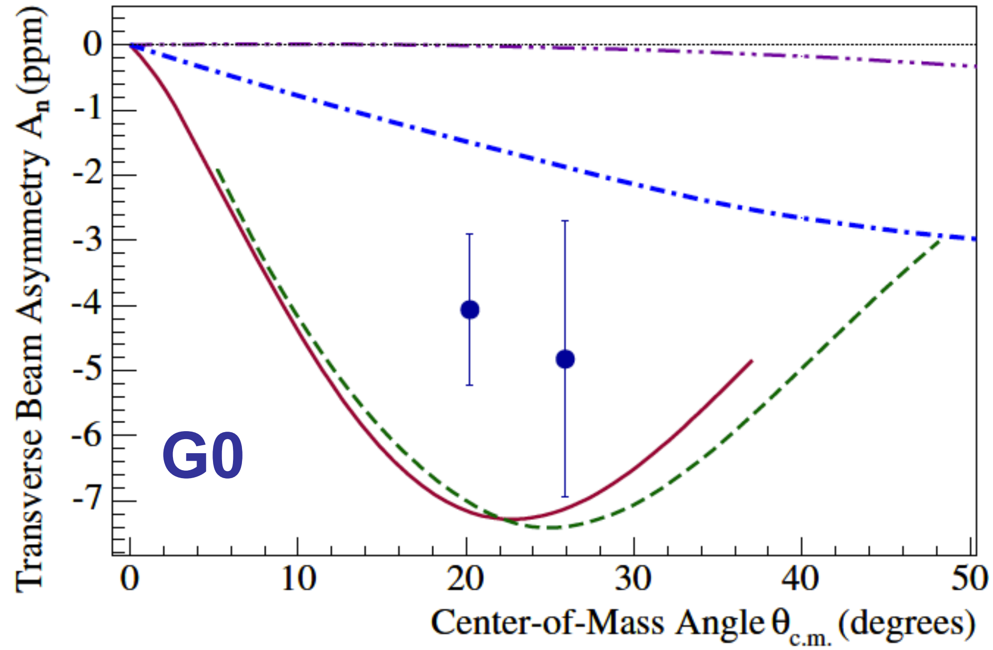
- Rosenbluth separation:
  - linear fit to extract FF ratio
  - second fit (not shown) with data shifted by δ_{slope} for systematics
  - $\Delta\sigma_{2\gamma}$ separates TPE size from G_E^2 slope



- this E05-017
- dashed: linear fit
- dotted: PTprediction

Beam-normal single spin asymmetry



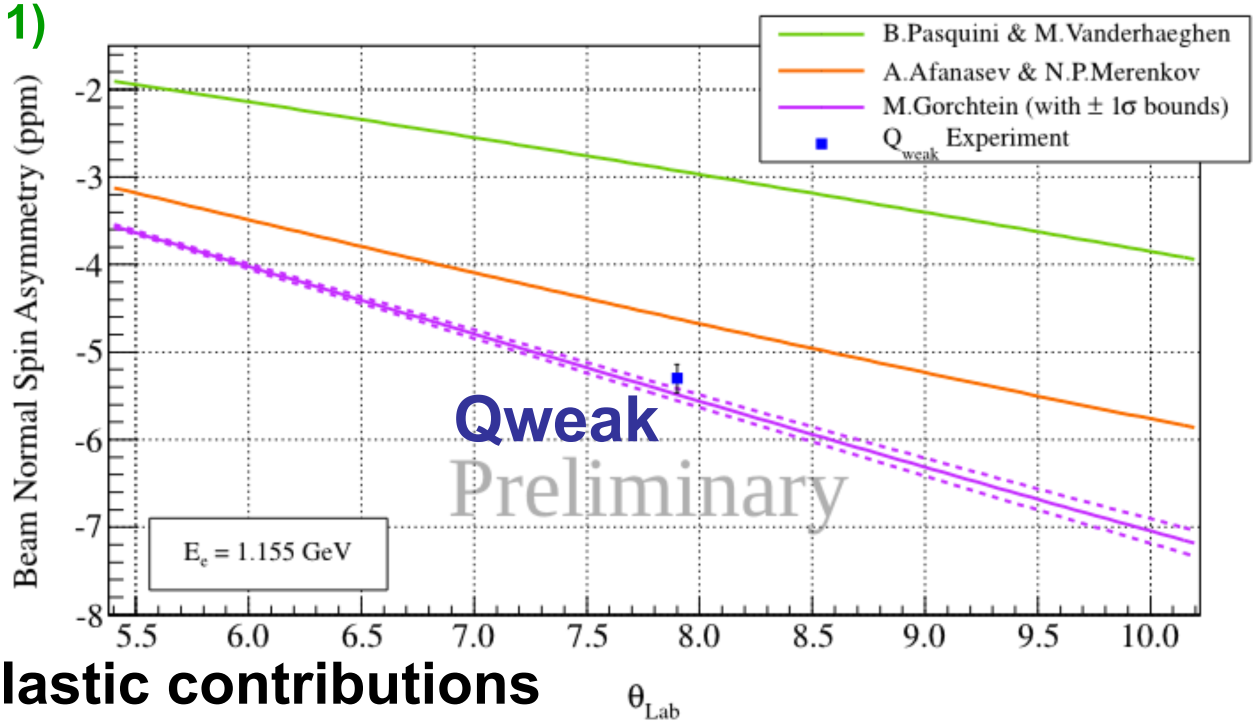


F. Maas *et al.*, PRL 99, 092301 (2005);
S. Baunack, EPJ ST198, 343 (2011)

D. Armstrong *et al.*, PRL 99, 092301 (2007)

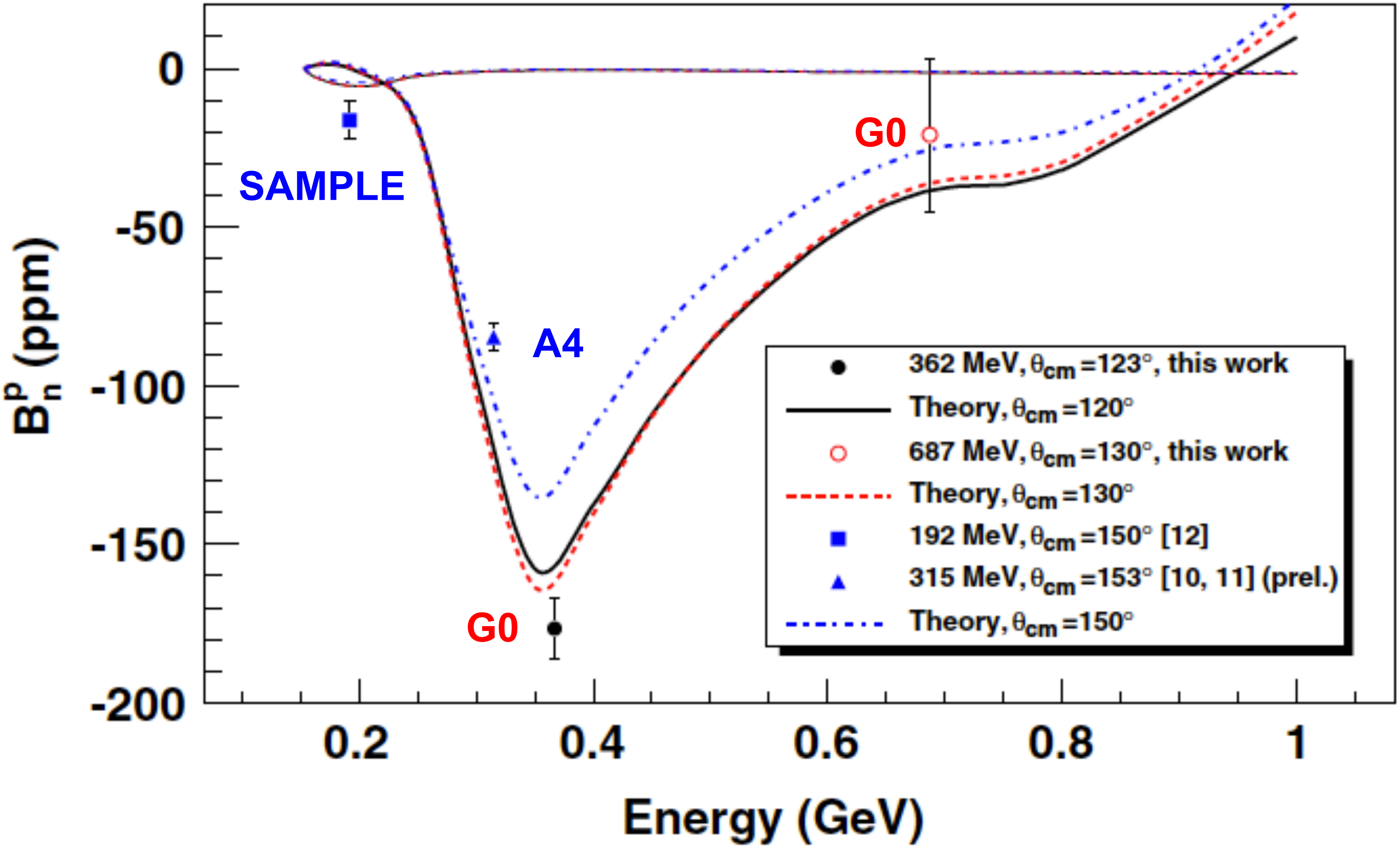
p(e⇧,e’) at forward angles

Qweak (preliminary):
A_n= (−5.35±0.07±0.15) ppm
B.P. Waidyawansa, PAVI2014, arXiv:1604.04602



BNSSA’s dominated by inelastic contributions

Beam-normal single spin asymmetry



p(e⇧,e') at backward angles:

G0 bwd: D. Androic *et al.*, PRL 107, 022501 (2011)

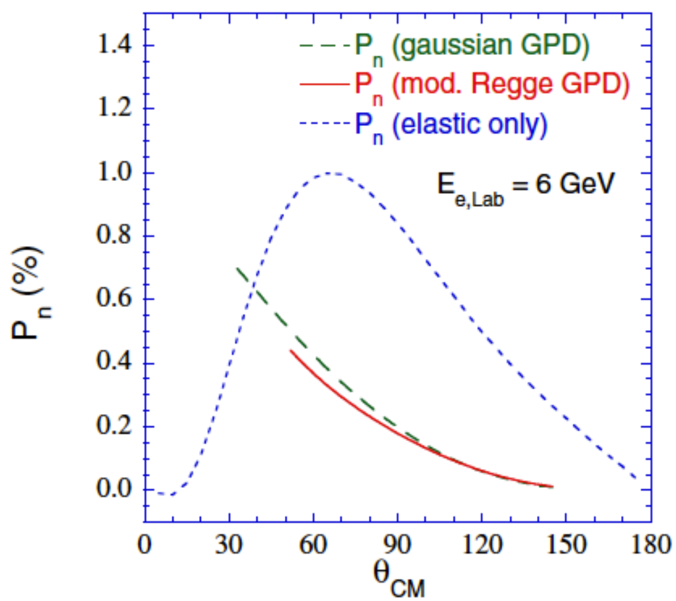
A4 bwd: S. S. Baunack, EPJ ST198, 343 (2011)

SAMPLE: S. Wells *et al.*, PRC 63, 064001 (2001)

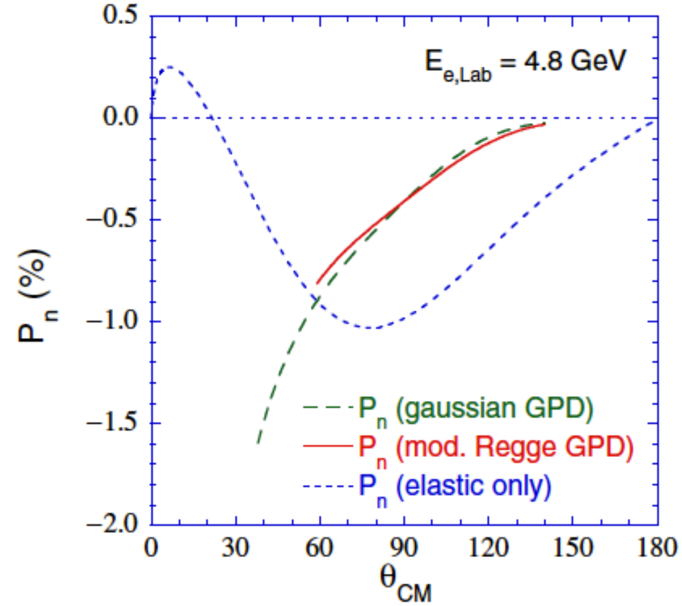
BNSSA's dominated by inelastic contributions

Target-normal single spin asymmetry

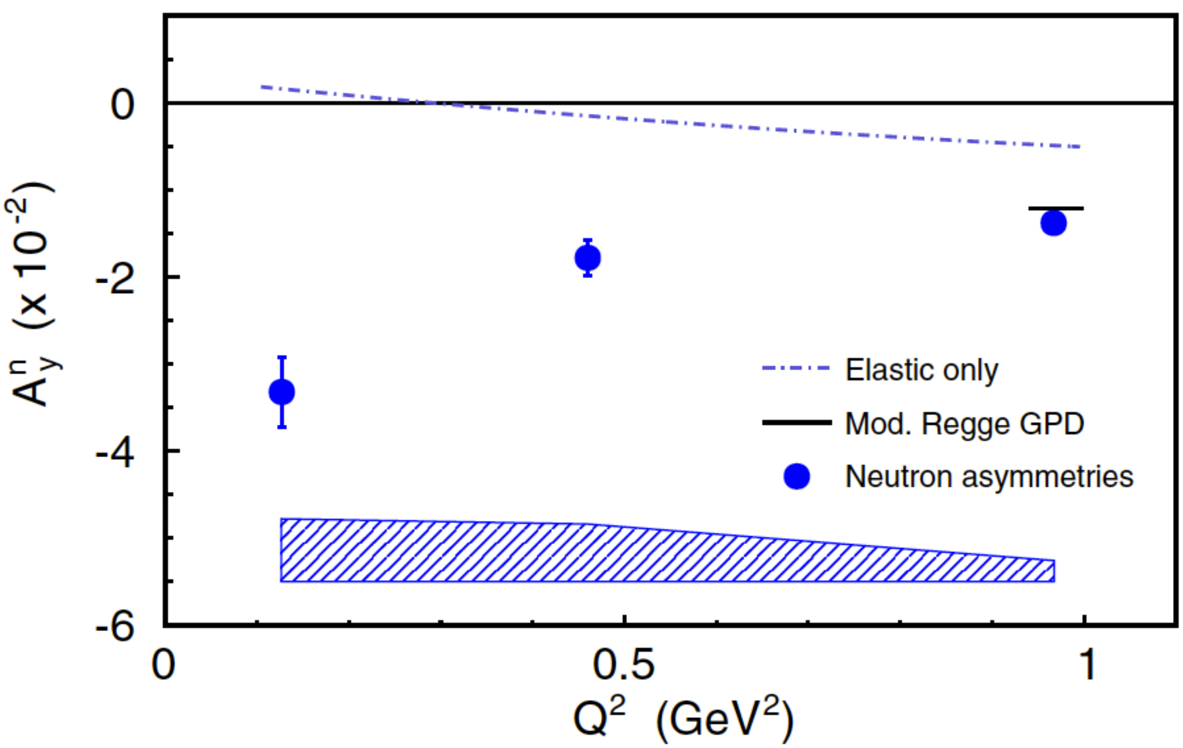
Normal Polarization or Analyzing Power - Proton



Normal Polarization or Analyzing Power - Neutron



A. Afanasev *et al.*,
PRD 72, 013008 (2005)
(elastic)
%-level asymmetries
opposite sign for p&n



^{3}He⇧(e,e'): E05-015 (quasielastic)

Y.-W. Zhang *et al.*,
PRL 115, 172502 (2015)

Theory:
Y.C. Chen *et al.*,
PRL 93, 122301 (2004)

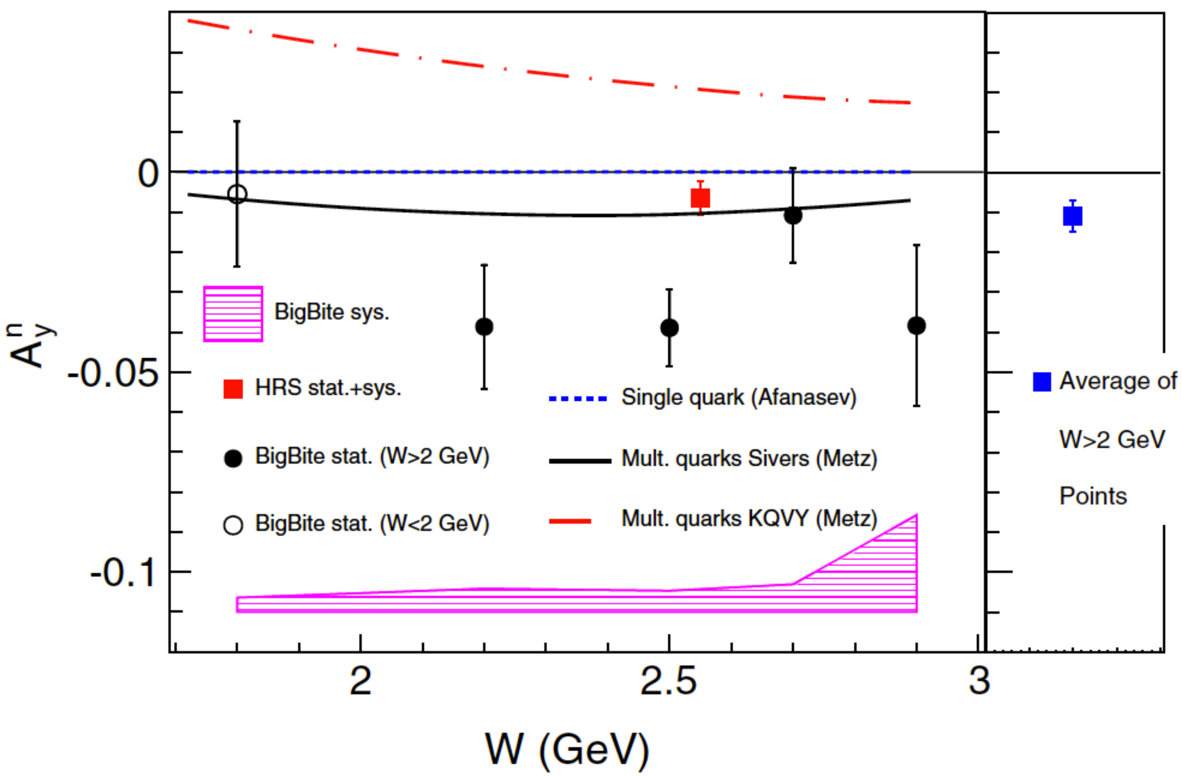
Further:

^{3}He⇧(e,e'n): E08-005 (quasielastic)

Target-normal single spin asymmetry

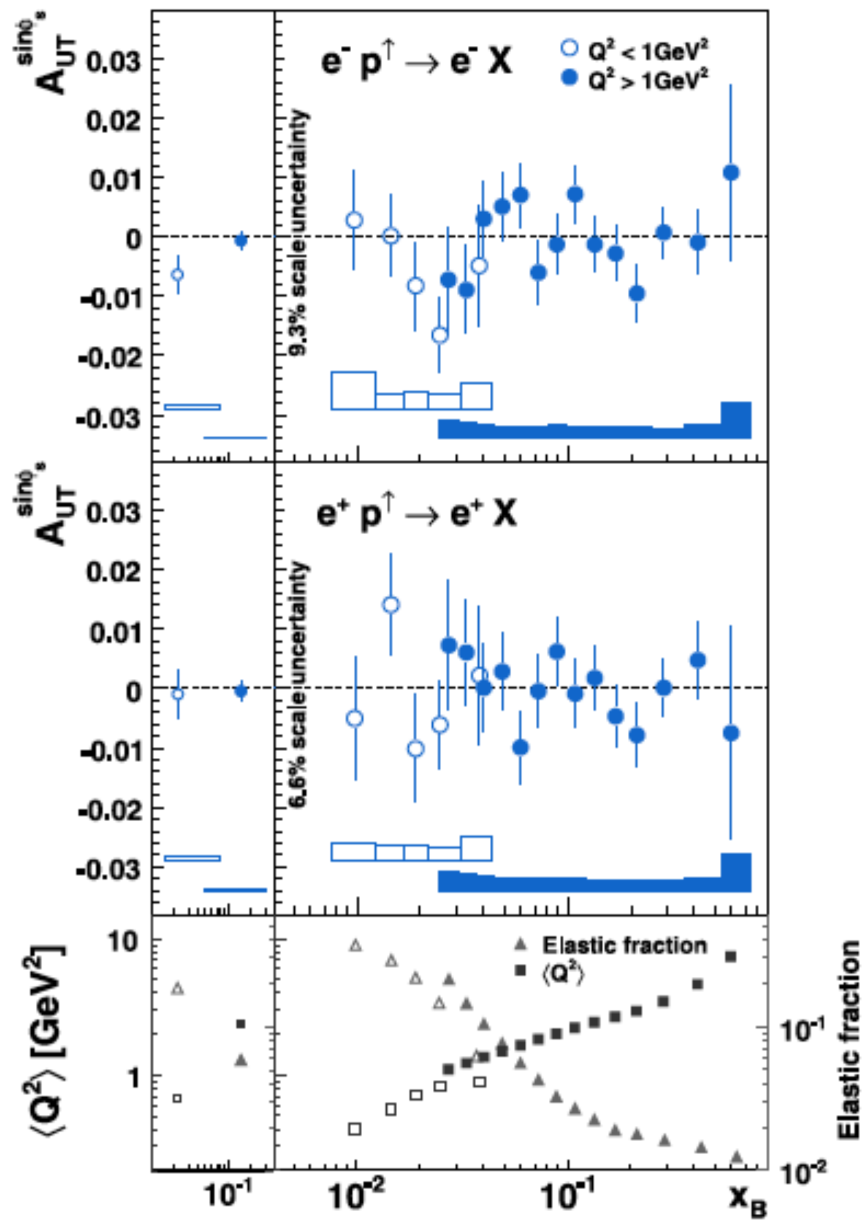
$^{3}He\Uparrow(e,e')X$: E07-013 (DIS)

J. Katich *et al.*, PRL 113, 022502 (2014)



$p\Uparrow(e,e')X$: HERMES (DIS)

A. Airapetian *et al.*, PLB 682, 351 (2010)



Single-quark: 10^{-4}-level asymmetries

A. Afanasev *et al.*, PRD77, 014028 (2008)

Multi-quark: %-level asymmetries

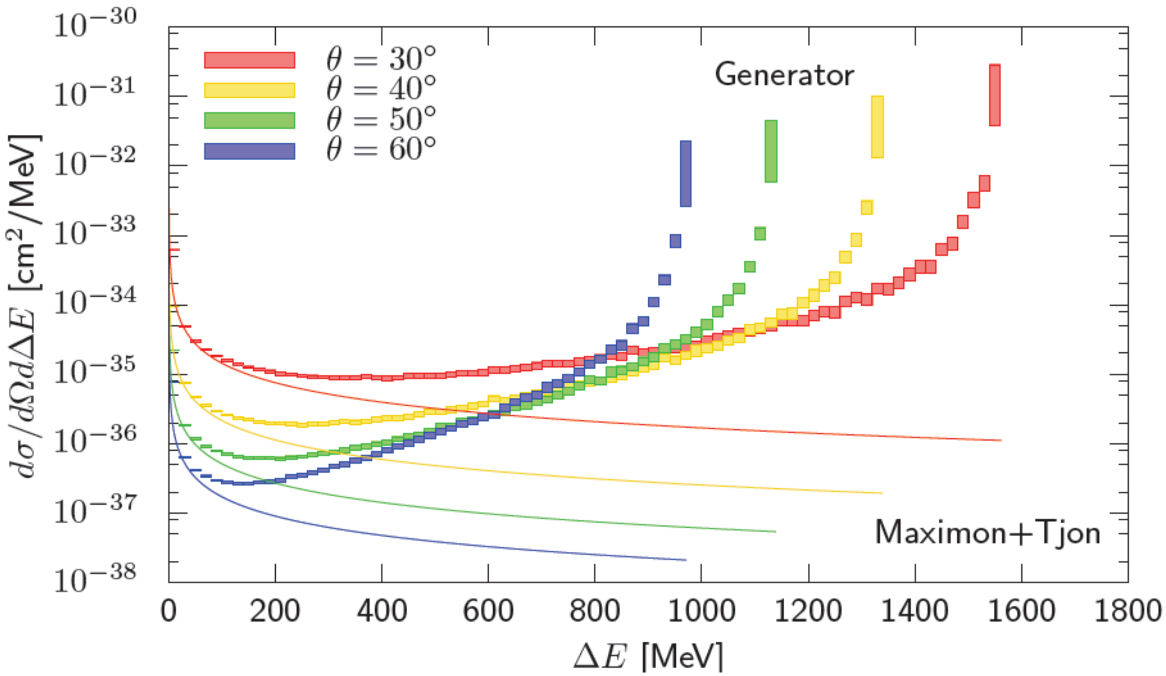
A. Metz *et al.*, PRD 86, 094039 (2012)

The OLYMPUS experiment

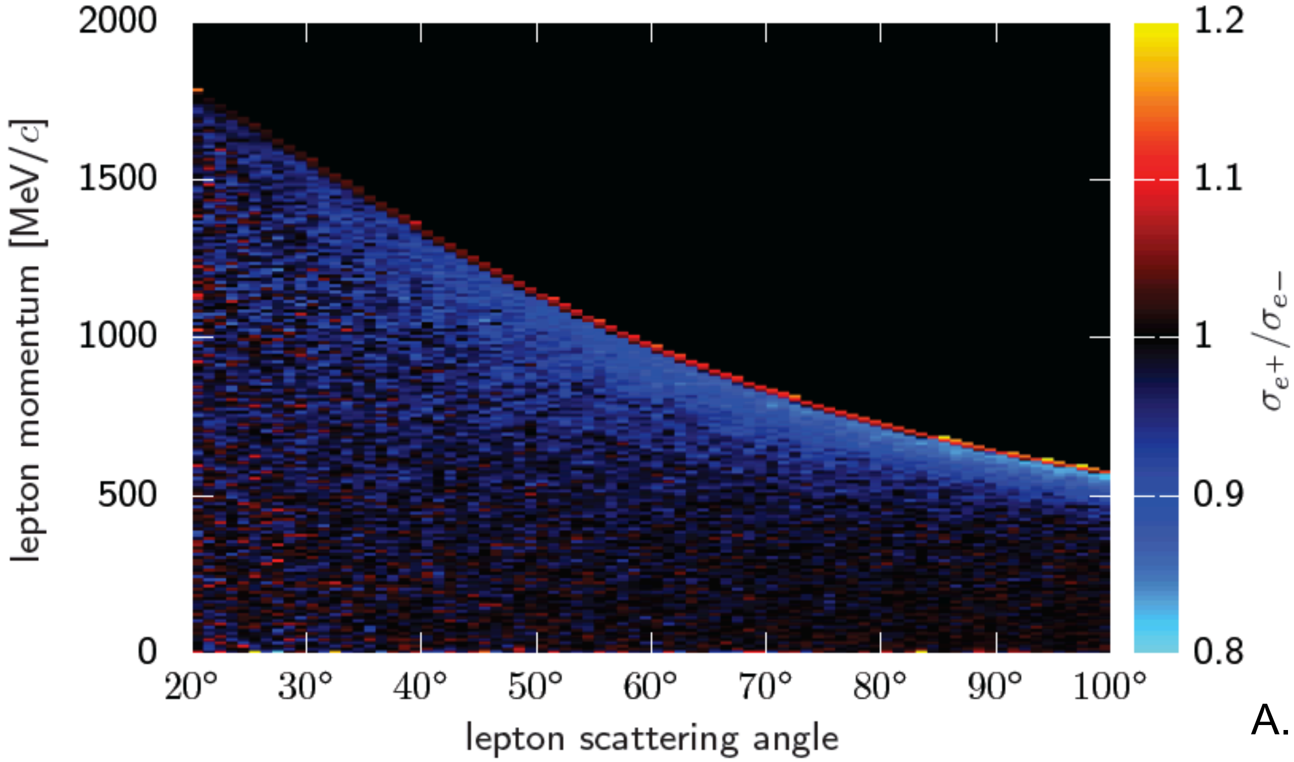
- Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring
  DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system)
  $3x10^{15}$ at/cm^2 @ 100 mA → L = $2x10^{33}$ / (cm^{2}s)
- Large acceptance detector for e-p in coincidence
  BLAST detector from MIT-Bates available
- Redundant monitoring of luminosity
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering

- **Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.**

MIT radiative generator



- Avoids approximations
- Agreement with Maximon&Tjon (soft photons) at low ΔE
- Excellent agreement with VEPP-3 generator at O(α^3)

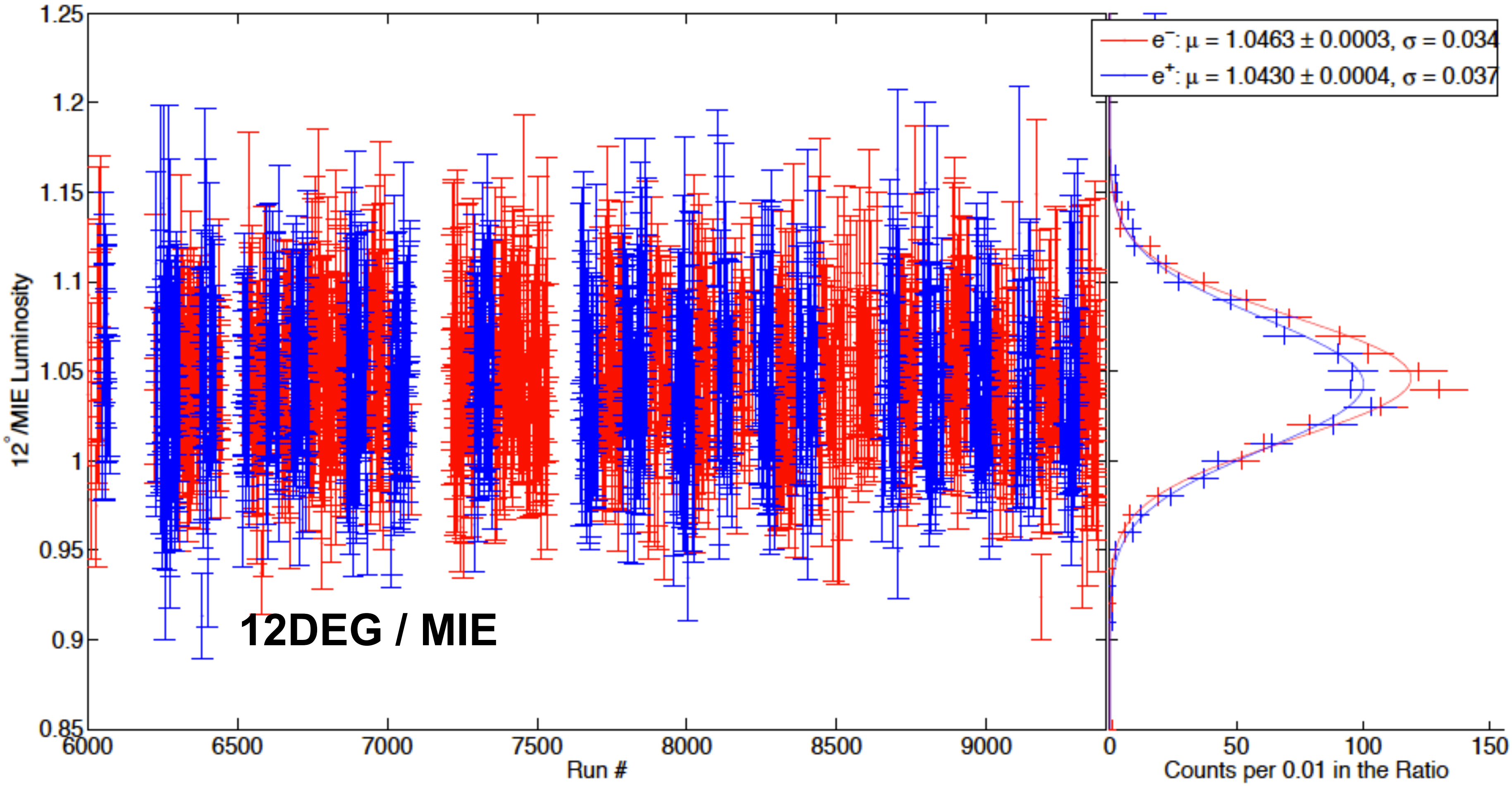


Effect on σ_{e+}/σ_{e-}

A. Schmidt, R. Russell, J. Bernauer (MIT)

Luminosity monitoring

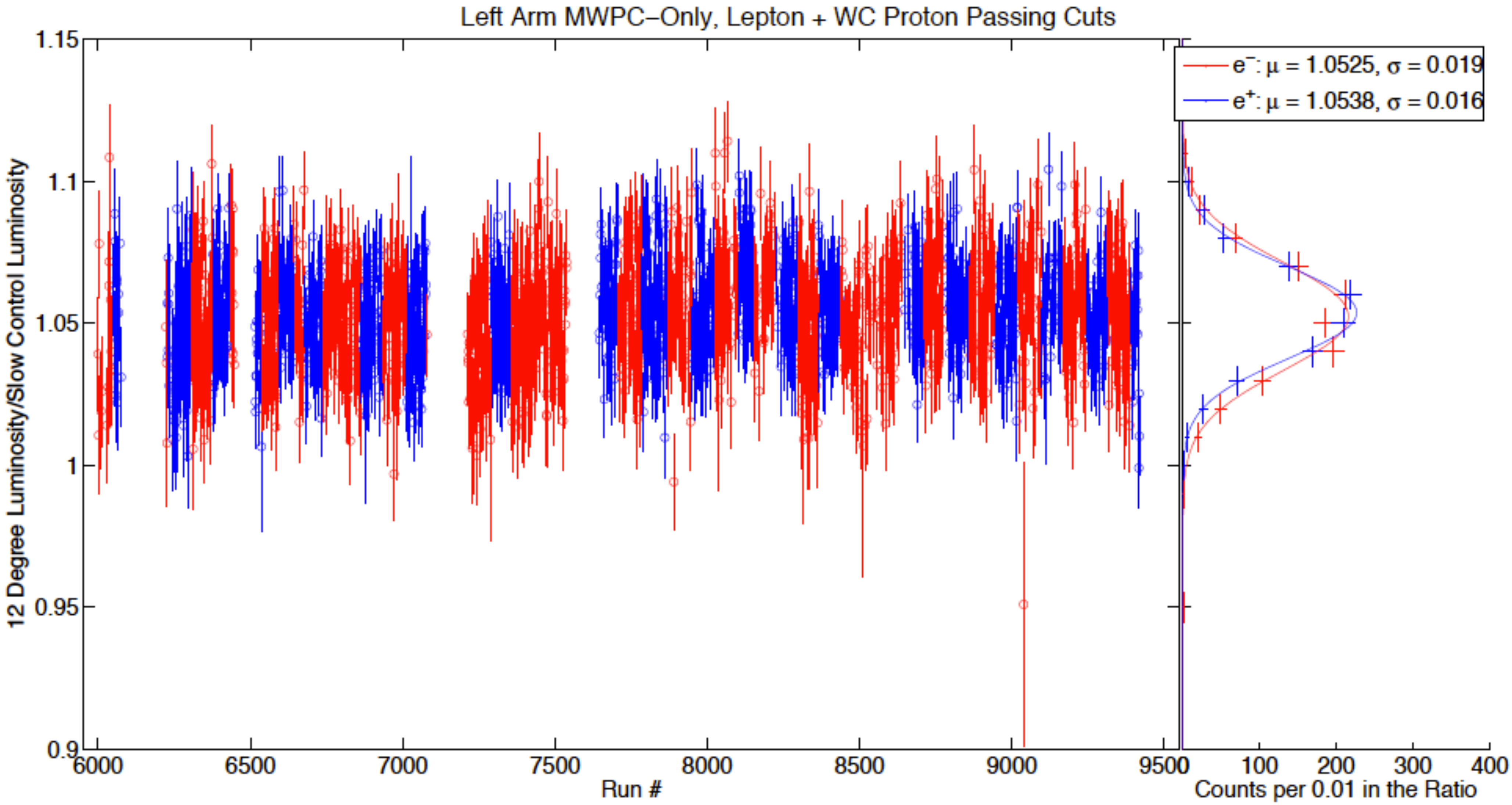
- Five redundant systems: Slow Control, SYMB, MIE, 12DEG-L,R
- Absolute luminosity from each rate to a few %
- Ratio of e^+/e^- luminosities for $R_{2\gamma}$ to sub %
- Time variation, mean and variance, systematics from comparisons
- Excellent agreement between SC, MIE, and 12DEG-L,R
- Final luminosity ratio from MIE, using 12DEG for high-ε data point



A. Schmidt, B. Henderson (MIT)

Luminosity monitoring

12DEG-L / SC

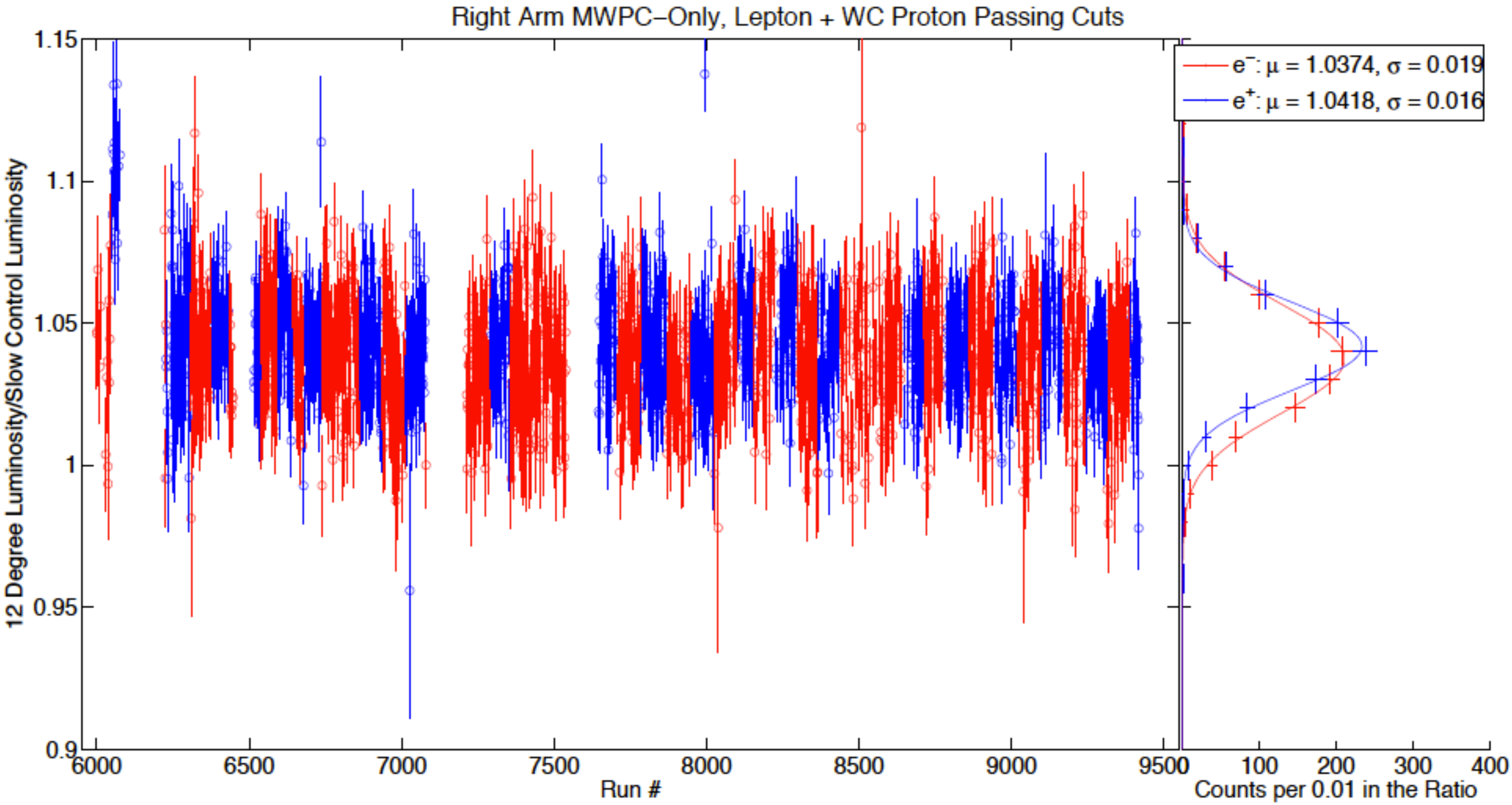


B. Henderson (MIT)

Luminosity monitoring

OLYMPUS

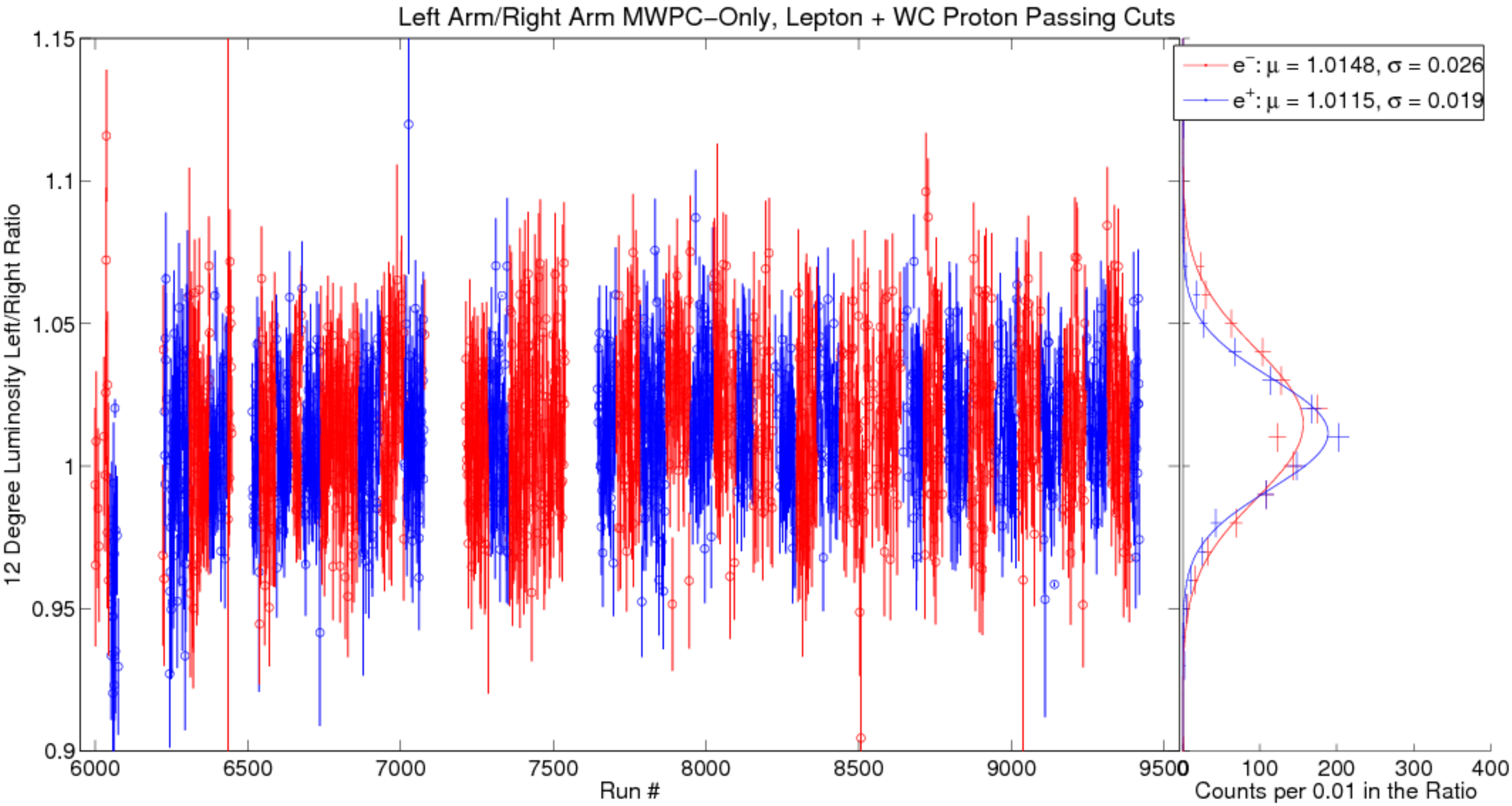
12DEG-R / SC



B. Henderson (MIT)

Luminosity monitoring

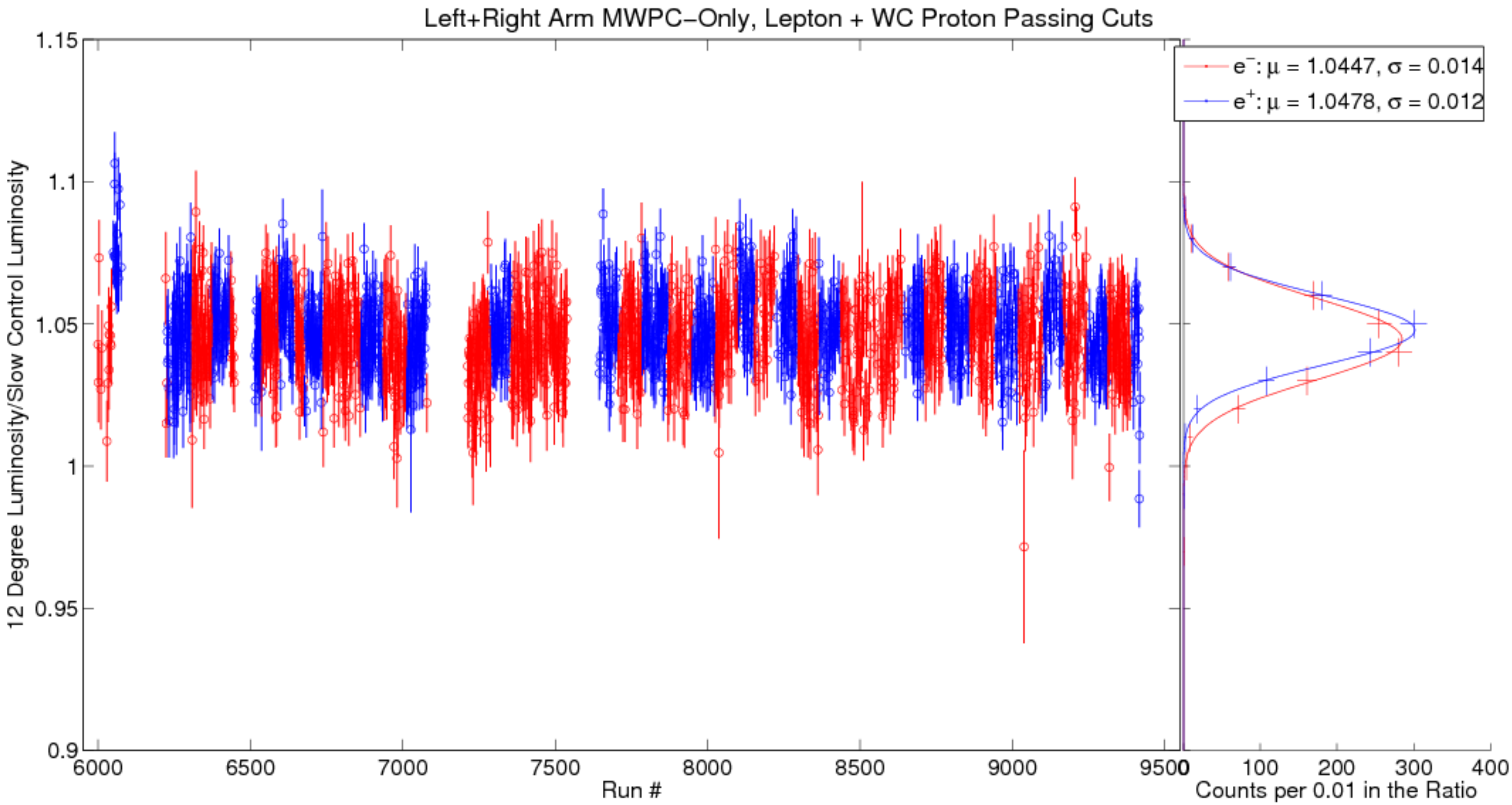
12DEG-L / R



B. Henderson (MIT)

Luminosity monitoring

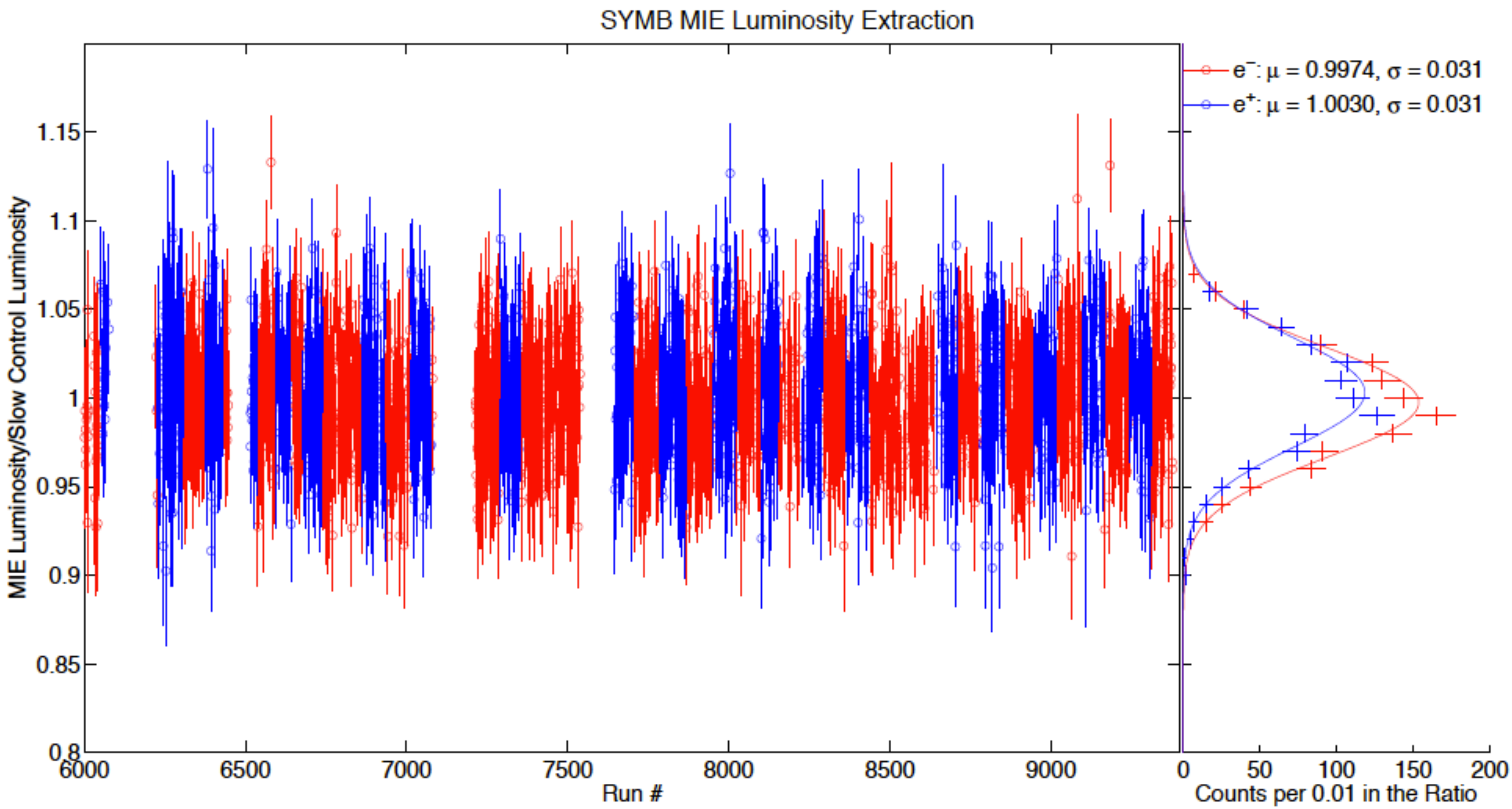
12DEG L+R / SC



B. Henderson (MIT)

Luminosity monitoring

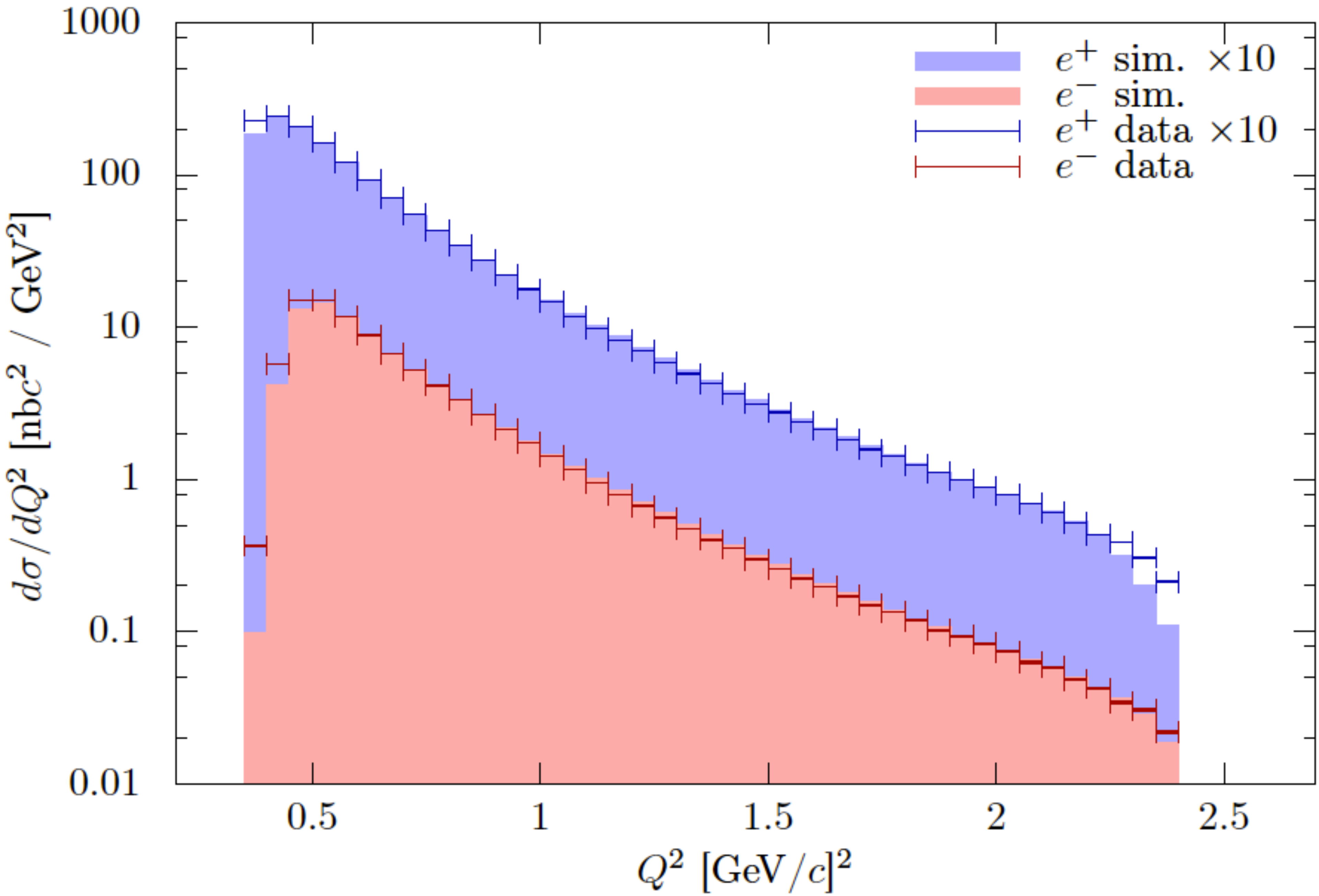
MIE / SC



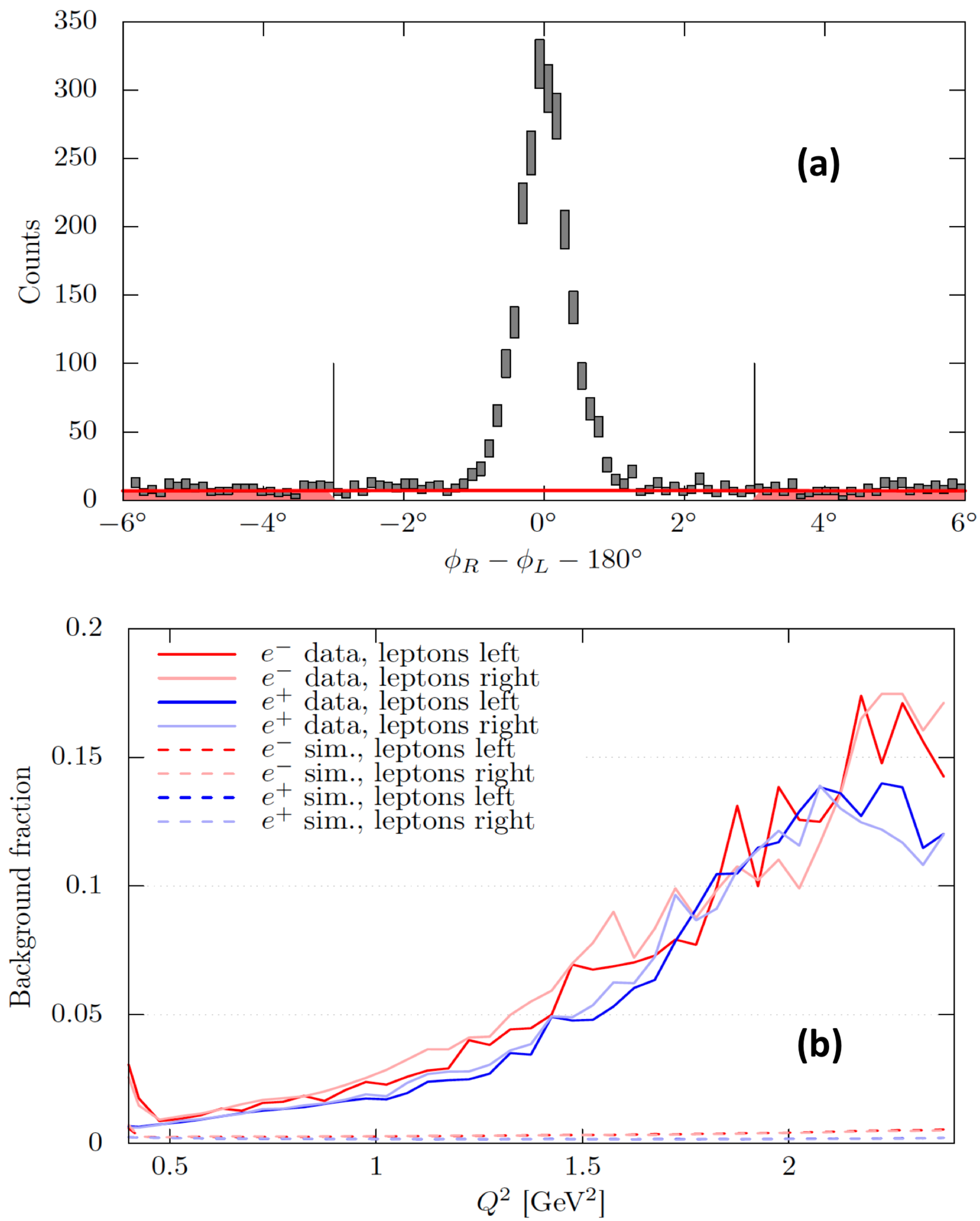
A. Schmidt, B. Henderson (MIT)

Yields

OLYMPUS

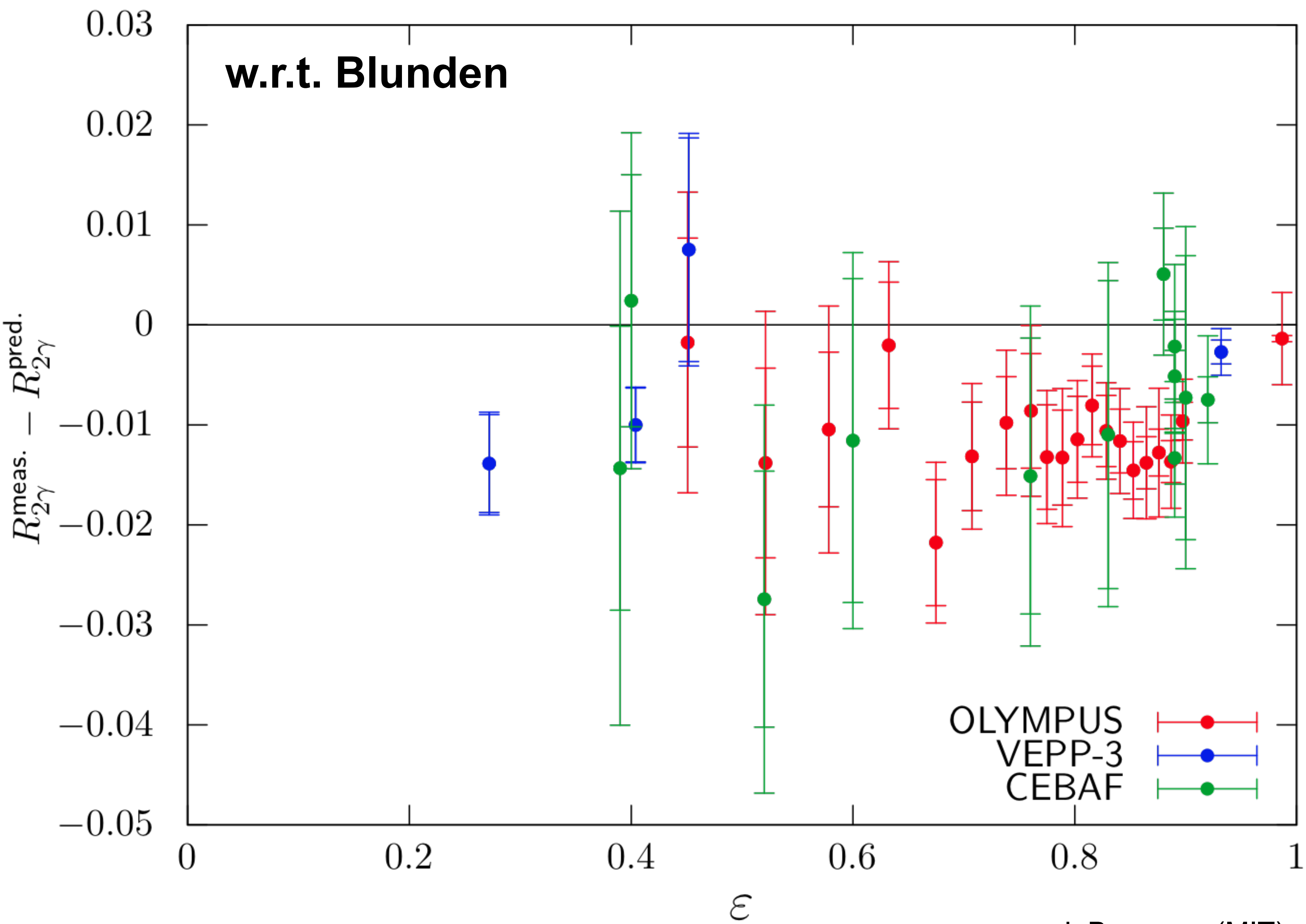


Backgrounds



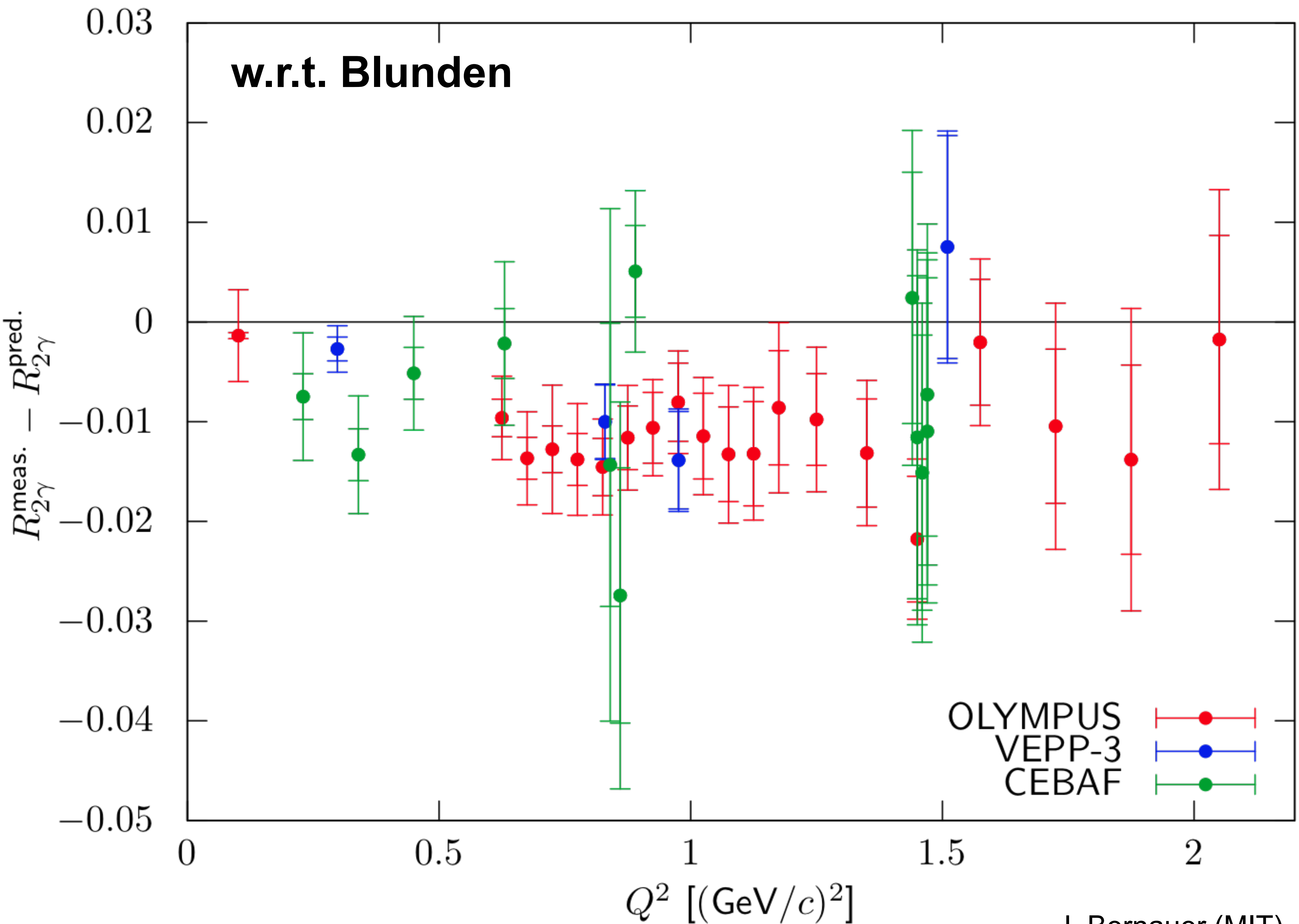
- **Coplanarity peak for background estimation**
- **Backgrounds range from negligible at forward angles to 15-20% at large angles**
- **Mostly independent of species**

Comparison with VEPP-3 and CLAS



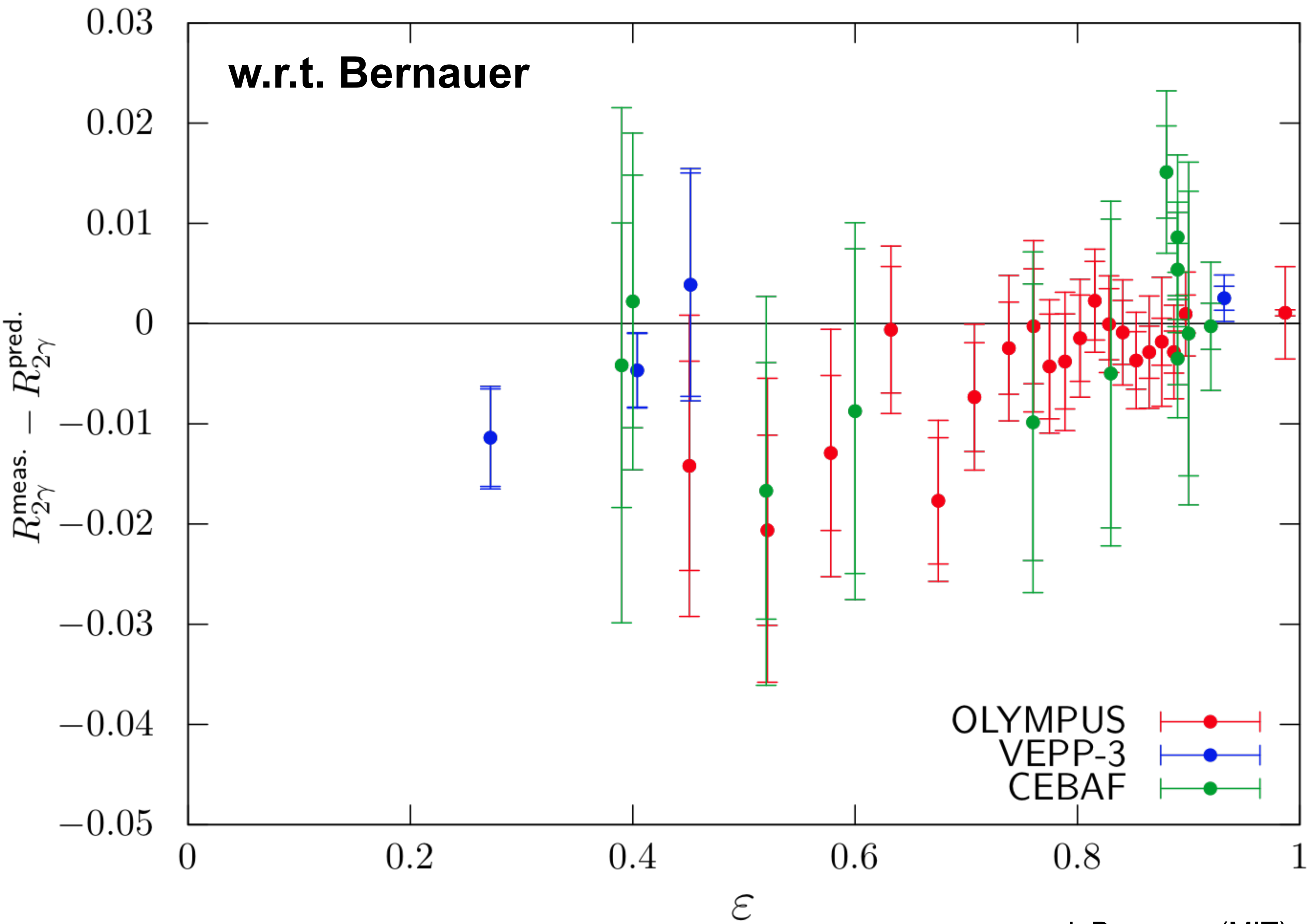
J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS